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THE INSTITUTE OF PETROLEUM

AN Ordinary General Meeting of the Institute was held at 26 Portland Place, London, W.1, on 11 February 1953, Mr R. B. Southall, vice-president, in the Chair.

THE CHAIRMAN said: The authors of to-night's paper, Mr C. S. Lee and Dr R. O. Young, have had extensive experience in Trinidad and Venezuela, which has prepared them for their Canadian work. They are not present, but their paper will be given by Mr E. Cooper Scott of Trinidad Leaseholds Ltd. and Mr R. A. McMullen, who is the Agent-General in the U.K. for the Province of Alberta. We are very grateful to them for the help they are giving us.

The following paper was then read:

ENTRY INTO OIL OPERATIONS IN WESTERN CANADA

By C. S. LEE * and R. O. YOUNG † (Associate Member)

SUMMARY

Since 1947, the progress and development of oil in Western Canada has become a matter of first importance to the oil industry in all parts of the world. This paper reviews the conditions under which this development is taking place and discusses legislative, financial, and practical problems which will face any company intending to participate. Particular attention is paid to the regulations governing the acquisition of reservations and leases from the Provincial Governments wherein the greater part of the mineral rights are vested. The geography, history, and constitution of Canada are related to the general development. A considerable section of the paper is devoted to the classification of the companies and the types of deals and negotiations which are conducted between them. It concludes with a comparison between the Western Canadian and the Venezuelan oil development.

GEOGRAPHIC FRAMEWORK

THE potential oil-producing belt of Western Canada (cf. Fig 1) extends over four provinces, Manitoba, Saskatchewan, Alberta, and British Columbia and the two territories, Yukon and the Northwest Territories. The east–west extent ranges from the Rockies to Southwestern Manitoba, about 700 miles, and narrows to less than 200 miles near the Arctic Ocean. In the northwest direction the belt extends 2000 miles.

CLIMATE

Climate ranges from arctic in the north to temperate (coastal) in the west and temperate (continental) in the east.

Despite the extremes in temperature, the general dryness of the climate alleviates its severity. The winterizing of drilling rigs is a simple and routine matter, and the main source of trouble in winter arises only in extreme cases when blizzards and the resulting drifting of snow causes local blockage of communications.

* President, Canadian Decalta Gas and Oils Ltd.
† Geologist, Trinidad Leaseholds (Canada) Ltd.

Temperature Ranges and Averages [1]

Locality	Yearly averages			Precipitation, inches	Sunshine, hr	Snow, inches	Frost-free period, days
	Max, °F	Min, °F	Mean, °F				
Lethbridge .	53	28	41	15·9	2369	42·2	115
Calgary .	50	26	38	16·4	—	43·5	94
Banff . .	47	24	36	19·4	—	77·1	—
Edmonton .	48	26	37	17·7	2145	42·5	87
Peace River	44	19	32	12·4	—	39·8	80

Communications

Roads

In view of the vast areas and distances, it follows that first class roads are limited. Second class " all weather " gravelled roads form fairly adequate secondary links, and dirt roads are found at 2-mile intervals running east–west and at 1-mile intervals running north–south in the settled areas.

In dry weather and winter these roads are readily passable; in wet weather transport is difficult, but—on balance—the road situation presents only minor nuisances. The aspects with regard to exploration drilling are as follows :—

(i) Best season is chosen, if necessary, summer or mid-winter.

(ii) In a " settled " area the length of new road required for a location is negligible, very different from South America or the East Indies.

(iii) In the remoter bush country winter operations are not difficult with suitable equipment. Timber is generally light and readily bulldozed aside.

Railways

The railways form an adequate grid, which was necessary before the advent of long distance heavy road transport. At the present time, the railways endeavour to keep their freight rates in line with the competitive road rates.

Air Transport

For personnel, air travel generally represents the most convenient mode of travel. Commercial flights link the main centres. In order to reach the remote northern areas " bush " services and unscheduled flights by major airlines provide convenient access. Major oil companies operate their own air transport system.

Survey System [2]

The Prairie Provinces are divided by six north–south meridians into five areas. The first meridian is in Manitoba, the fourth on the Saskatchewan–Alberta boundary, and the fifth and sixth in Western Alberta.

The areas between the meridians are divided into " ranges," each 6 miles wide, by lines running north–south, and the ranges are numbered from east to west. Each range is cross-divided by " township " lines which run

LABRADOR
QUEBEC
MONTREAL
MAINE
VERMONT
NEW HAMPSHIRE
MASSACHUSETTS
CONN.
TORONTO
BUFFALO
NEW YORK
DETROIT
CLEVELAND
PENNSYLVANIA
NEW JERSEY
TOLEDO
OHIO

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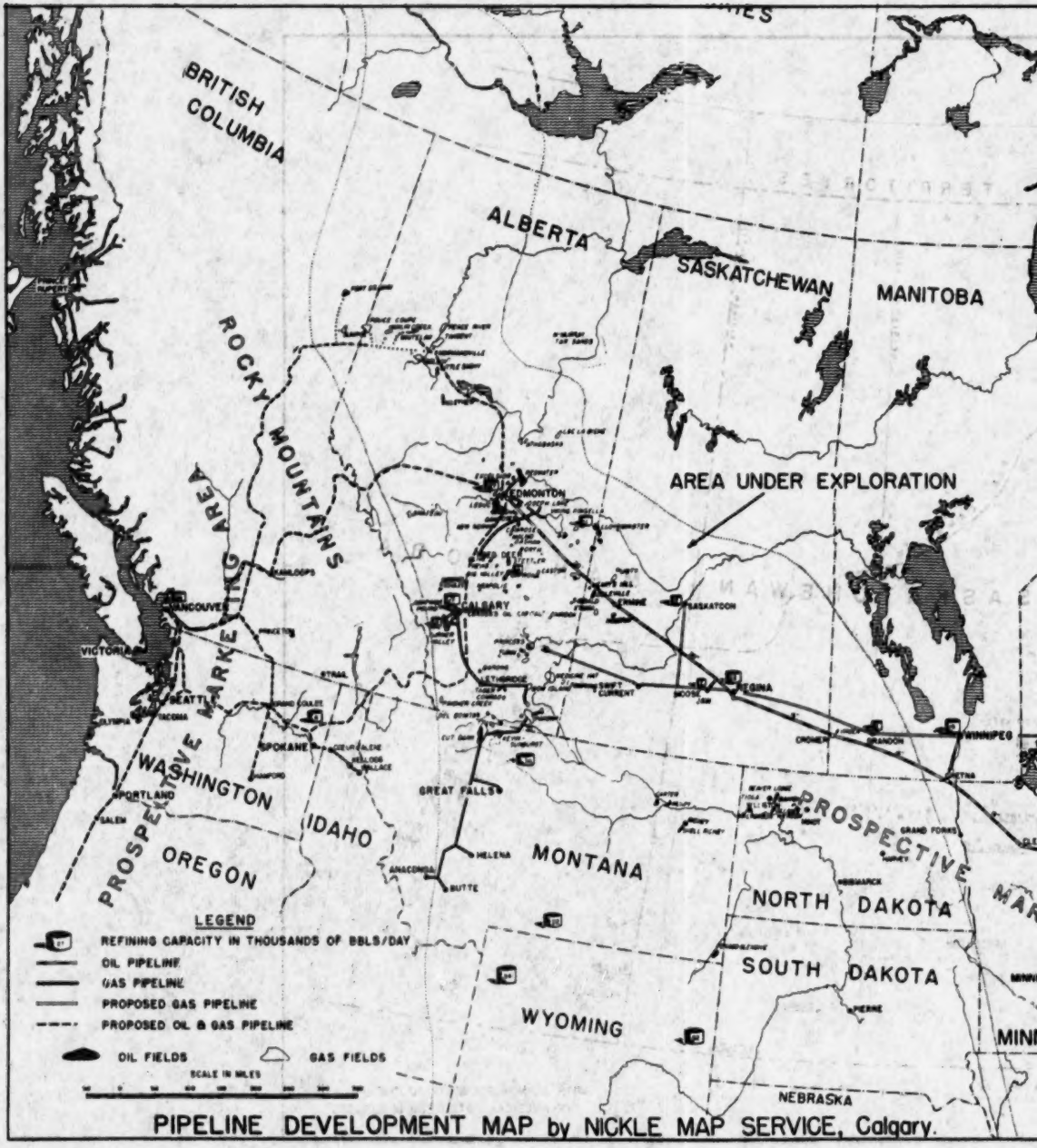

FIG 1

OIL DEVELOPMENT MAP OF WEST

WESTERN CANADA

[To face p. 384.

GREAT SLAVE LAKE
NORTHWEST
BRITISH COLUMBIA
ALBERTA
SA
MONTANA
NORMANDVILLE
STURGEON LAKE
APPROX. EDGE OF FOOTHILLS
EDMONTON
REDWATER
BONNYVILLE
VERMILION
WAINWRIGHT
CARBONDALE
ACHESON
LEDUC
WOODBEND
LEDUC-WOODBEND
SOUTH CALMAR
WIZARD LAKE
BONNIE GLEN
JOSEPH LAKE
CAMROSE
DUHAMEL
NEW NORWAY
SCURRY
BASHAW
CLIVE
ESTHER
PINE LAKE
FENN
BIG VALLEY
ELNORA
DRUMHELLER
CHANCELLOR
JUMPING POUND
CALGARY
CROSSFORD
TURNER VALLEY
PRINCESS
BARONS
TABER
CONRAD
SPRING COULEE
WINDER CREEK
MAP OF
WESTERN CANADA
SHOWING
NEW OIL FIELDS
DISCOVERED IN 1951-2 AND
IMPORTANT BASEMENT TESTS
New Fields Underlined as WIZARD LAKE
ABANDONED Well - Reached Basement
See Supplement No. I
Scale in miles

TERRITORIES
PRE-CAMBRIAN
SASKATCHEWAN
MANITOBA
LAKE
WINNIPEG
PRINCIPAL MERIDIAN
SASKATOON
REGINA
WINNIPEG
BRANDON
VIRDEN
SWIFT CURRENT
FOSTERTON
COLEVILLE
NORTH DAKOTA
WITH ACKNOWLEDGMENTS TO THE BULLETIN
OF AMERICAN PETROLEUM GEOLOGISTS

Fig 4

Temperature Ranges and Averages [1]

Locality	Yearly averages			Precipitation, inches	Sunshine, hr	Snow, inches	Frost-free period, days
	Max, °F	Min, °F	Mean, °F				
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east–west and are 6 miles apart. Townships are numbered from 1 at the U.S. boundary to 113, the current northern edge of " surveyed " areas in Northern Alberta. In every four townships there is a shift in the ranges due to meridian corrections.

The thirty-six sections in a township are each given a number and are arranged as shown in Fig 2. Each section contains 640 acres, measures 1 mile by 1 mile and is divided into sixteen legal subdivisions numbered as

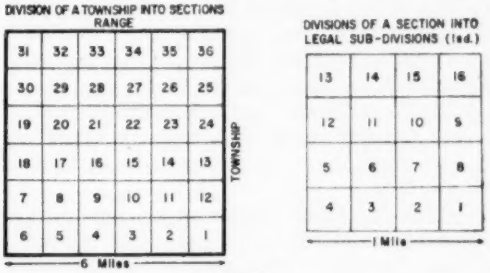

DIVISION OF A TOWNSHIP INTO SECTIONS
RANGE
31 32 33 34 35 36
30 29 28 27 26 25
19 20 21 22 23 24
18 17 16 15 14 13
7 8 9 10 11 12
6 5 4 3 2 1
TOWNSHIP
6 Miles
DIVISIONS OF A SECTION INTO
LEGAL SUB-DIVISIONS (Ind.)
13 14 15 16
12 11 10 9
5 6 7 8
4 3 2 1
1 Mile

FIG 2

in Fig 2. The legal subdivision is the present normal well spacing unit. Position of a well within the legal subdivision is measured as so many feet north or south and east or west of the sides of the containing section.

POLITICAL FRAMEWORK

Whilst a complete review of the history of the settlement of Canada would be largely irrelevant to a paper of this character, the progress of settlement across the Canadian prairies from east to west, and the correlation of that progress with legislation affecting mineral rights, has had a profound effect, first, upon the ownerships of mineral rights and, second, upon the certification of title in the different Western provinces.

The aggressive development of the Hudson's Bay Company and the Canadian Pacific Railway has also left an imprint on the lease pattern of the Prairies; both Hudson's Bay and the Railways were made substantial, widely scattered grants of Crown lands, which included the mineral rights, in return for their immense development programmes.

When confederation took place in 1867, only four provinces, Ontario, Quebec, New Brunswick, and Nova Scotia were present. They were joined by Manitoba in 1870, British Columbia in 1871, Prince Edward Island in 1873, Saskatchewan in 1905, and Alberta in 1905.

In 1857 was enacted the Torrens Act (covering the Torrens System of Land Titles Registration). In 1889 the Crown alienated the Mineral Rights. In 1930 the Natural Resources Act vested the natural resources in the Province as distinct from the Dominion. The exceptions to this were the Dominion Parks and Indian Reserves.

The chronology of these events affected the provinces in a variety of ways.

Manitoba was settled before the mineral rights were alienated; accordingly, much of the prospective oil land is " freehold " and the farmers have the oil rights. The title to the land is only partly regulated by the Torrens System and partly by a rudimentary deed recording process, which makes title search a difficult task.

Saskatchewan was less settled when lands were alienated; consequently, approximately 30 per cent is freehold mineral rights and 70 per cent is Crown mineral rights. The Torrens System applies.

Alberta was even less settled : 14 per cent is freehold mineral rights (16,000,000 acres); 86 per cent is Crown mineral rights (132,620,070 acres), and the Torrens System applies.

The Hudson's Bay Company retained one and three-quarter sections with mineral rights in each township, when it surrendered its grant of Ruperts Land. (In Alberta, the Company has 1,500,000 acres.)

In 1881 the Canadian Pacific Railway Company and its Associates received land grants in consideration for the construction of the railways, and the Dominion Government granted them 25 million acres of land together with the mineral rights in the lands which are now Alberta, Saskatchewan, and Manitoba. (In Alberta, the Company has 13,031,731 acres.)

Apart from British Columbia, where the regulations governing the prospecting and exploitation of oil have some slight relation to the Colonial Model Regulations, Petroleum and Natural Gas Regulations in Alberta, Saskatchewan, and Manitoba are radically different from those which prevail in territories where British companies are accustomed to operate. Except in the National Parks and Indian Territories, the Federal Government is in no way involved.

The Federal Government exacts income tax and levies customs duties and sales taxes, while the Provincial and Municipal Governments exact property taxes, city taxes, mineral taxes, sales taxes, increment taxes, fuel oil, and gasoline taxes.

Background of the Petroleum Industry in Western Canada

Brief History of Oil Development

The discovery of Leduc in 1947 was the most important event in the development of Western Canadian oil, but earlier, less important discoveries paved the way for a rapid development.

Pre-Leduc. In 1914 minor oil production was found at 2500 ft by the Dingman well in Turner Valley, and more important wet gas and condensate accumulations were found in deeper beds in 1924. In 1936 major crude oil reserves were found in the same area. The gradual development of this field in the geologically complicated foot-hills served to stimulate search in the plains to the east, but for years, up to 1947, millions of dollars were spent with only minor success. The discoveries included several gas fields, some of which were exploited for local use; several minor medium-gravity oil pools at Princess, Brooks, Taber, and Conrad and what has subsequently developed into an important heavy oil pool at Lloydminster. Up to 1947, several companies had spent many millions of dollars each; all were beginning to despair, and some were withdrawing from the scene.

Meanwhile, the determined operations that had been conducted led to the establishment of general facilities, while suitable legislation and control based on experience were practised and tested before Leduc started the oil boom. There was also a great local and Dominion-wide need for additional oil, and in the U.S. there were oil development companies of all

sizes, together with service organizations ready to step in once reasonable prospects were offered. A refinery capacity of 50,000,000 brl per year was available, of which Alberta could satisfy only about 17 per cent.[3]

British capital had expended some effort during the fruitless years, but with one major exception, activity had dwindled, and when the opportunity for increased interest arrived in 1947, currency difficulties were acute and hindered participation.

Post-Leduc. The long string of important successes that followed the discovery of light oil in Leduc field in February 1947 and Redwater in August 1948 is well known. Summary data of the most important discoveries to date is included in Table I, while Fig 3 shows the statistics of the development of the Alberta oil industry.

The richest fields per unit are found in the Devonian biohermal reefs, where extremely thick and porous pay zones may be encountered, ranging up to several million barrels per well. It is important to realize that such reserves are confined to these local " D-3 " pools and that they have given rise to fantastically high lease prices for even unproven acreage where there are some prospects of such production.

Next in importance are the Devonian " D-2 " biostromal reefs and stratigraphic traps in the Cretaceous Viking sands, which carry recoverable reserves up to 200,000 or 300,000 brl per well, with an average of about 100,000 brl. Particularly for the " D-2 " with 5000-ft drilling depth and restricted production, the profit is limited, but proven acreage of this type fetches very high prices—of the order of $0·50 per barrel of undrilled recoverable reserves.

The Lower Cretaceous Sands (including the " Basal Quartz " or " Ellerslie Sand ") contain gas associated with oil in stratigraphic traps; wells are sometimes difficult to complete and may develop high gas : oil ratios. Range of oil types is described by Warren Hunt.[4]

Relative Importance of Light Oil, Heavy Oil, and Gas

While light oil (higher than 30° API) is the main object of search, due to its good local market price, on the other hand, gas discoveries are three times as frequent as oil discoveries. The degree to which gas can be utilized therefore influences the economics of oil search. Generally speaking, it is possible to predict whether heavy or light oil will be found, and company policy dictates areas of interest.

Light Oil

Speed of development depends on distribution facilities. If enough oil is present, a pipeline will be speedily constructed.

Heavy Oil

Generally speaking, the reserves of heavy oil are small in comparison with those of light oil, and they have so far served rather restricted and local markets. There are indications that more important heavy to medium oil reserves will be built up in Southwest Saskatchewan.

Gas

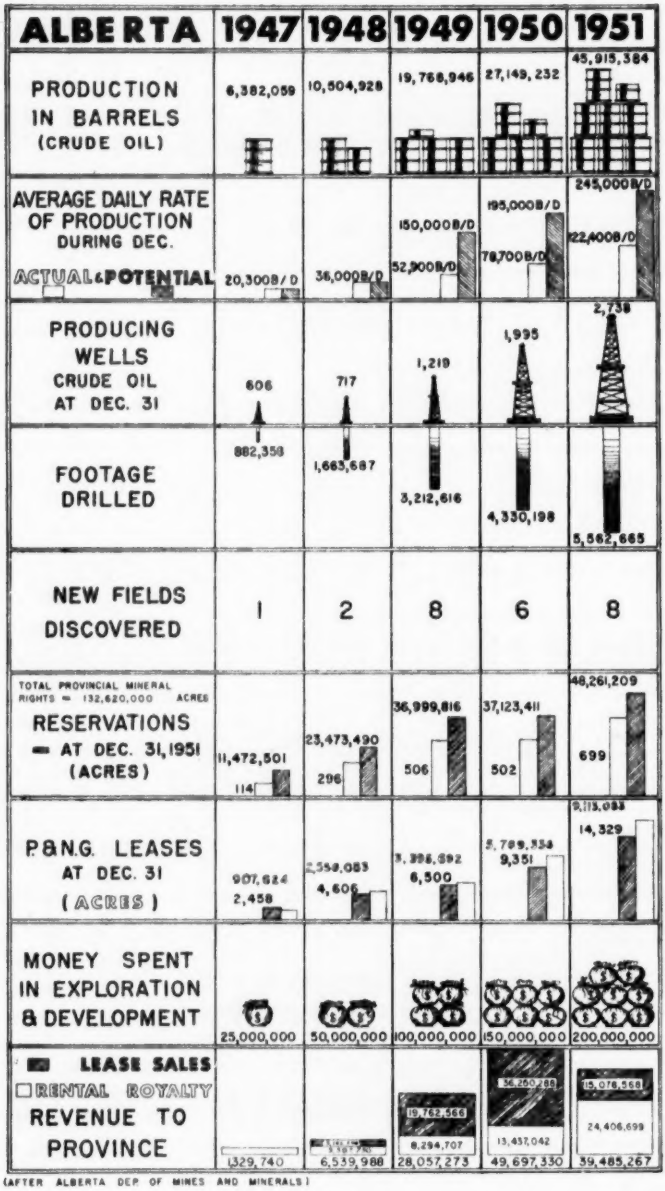
Albertan gas reserves are now more than adequate to serve future requirements; consequently export westwards to British Columbia and

Western Canadian Oilfield Statistics
(Based on Data from references 2 and 15)

Field	Date of discovery	Number of producing wells, 31.7.52			Producing horizon				Gravity of oil ° API	Price per brl, 31.7.52	Daily allowable b.d. Aug. 52	Total production, brl	
		Actually producing	Capable of producing	Ultimate no. of wells †	Formation	Approximate depth ft	Average pay zone thickness ft	Recovery factor †				Since discovery to 31.7.52	Estimated ultimate
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Acheson-Stony Plain	1950	6	7	—	L. Cret.	4,320	—	—	—	2·39	65 & 39	36,932	—
		76	77	80 †	Dev. D-3	5,000	80	45%	37–38	—	87	1,860,942	62,460,000
		5	6	—	Dev. D-2	—	—	—	—	—	40	22,148	—
Alliance . .	1951	2	—	—	L. Cret.	3,150	15	—	26	0·88 •	—	11,658	—
Armena . .	1951	46	46	—	Viking (Cret.)	3,260	20	—	37	2·25 •	60	273,409	—
Armisie . .	1951	8	8	—	L. Cret.	—	—	—	38	2·39	50	85,372	—
Barons . .	1950	3	3	—	Viking	4,110	2	—	—	—	—	42,502	—
Barrhead . .	1949	—	2	—	Madison	4,000	130	—	22–24	2·37 •	—	4,857	—
Bashaw . .	1951	1	1	—	Dev. D-3	5,800	19	—	39	—	43	42,141	—
Baxter Lake . .	1951	1	1	—	Colony Sd.	2,150	—	—	19	—	—	2,472	—
Belloy . .	1951	1	1	—	Permo Penn.	4,110	8	—	28	—	—	2,136	—
Big Valley . .	1950	28	30	65 †	Dev. D-2	—	40	0%	30–34	1·95 •	73	369,855	4,400,000
		7	7	10 †	Dev. D-3	5,400	21	0%	—	—	42	96,052	1,168,000
Bon Accord . .	1949	9	9	—	Dev. D-2	3,600	40	—	35	2·49 • At Redwater	—	64,732	—
Bonnie Glen . .	1951	7	7	—	Dev. D-3	7,070	—	—	—	—	346	169,121	—
Bonnyville . .	1951	6	8	—	Colony Sd.	1,170	—	—	—	—	G.F.P.	24,707	—
Camrose . .	1951	34	35	—	Viking	3,200	10	—	38	2·21 •	50	154,684	—
Campbell . .	1949	11	14	43 †	L. Cret.	3,700	15	0%	30–33	2·50 • At Redwater	38	153,859	10,500,000
Caprona (Fenn) .	1951	13	13	—	Dev. D-2	5,300	80	—	30	—	—	131,890	—
Cessford . .	1951	—	3	—	L. Cret.	3,280	—	—	26	0·94 • Pollockville	G.F.P.	6,814	—
Clive . . .	1951	4	4	—	Dev. D-2	6,200	12	—	39	2·26 • Calgary	G.F.P.	18,578	—
Coleville (Sask) .	1951	—	—	—	L. Cret.	2,720	60	—	14	—	G.F.P.	209,220	—
Coutts . . .	1951	—	1	—	L. Cret.	2,600	—	—	—	—	G.F.P.	—	—
Didsbury . .	1951	—	1	—	Madison	8,180	30	—	53	—	—	552	—
Drumheller . .	1950	1	3	—	L. Cret.	4,450	40	—	32–35	—	39	9,416	—
	1951	9	9	—	Dev. D-2	5,420	30	—	—	2·25	72	88,635	—
Duhamel—Flint .	1950	7	9	40 †	Dev. D-2	4,500	40	30%	34–35	2·21	78	98,876	6,435,000
		8	9	40 †	Dev. D-3	4,800	56	35%	—	—	72	240,742	12,135,000
East Edmonton (Chamberlain) .	1951	1	2	—	L. Cret.	3,725	15	—	—	—	—	8,515	—
Ellerslie. . .	1951	6	6	—	Viking (Cret.)	—	—	—	—	—	—	—	—
					L. Cret.	4,000	28	—	30–33	—	39	47,409	—
Excelsior . .	1949	34	35	40 †	Dev. D-2	3,846	67	40%	35–36	2·25	94	1,483,819	14,590,000
Fosterton (Sask) .	1952	1	9	—	L. Cret.	3,100	—	—	20–24	—	—	—	—
Glenevis . .	1951	—	—	—	Mississ.	4,330	25	—	18	—	—	—	—

Golden Spike	1949	2	2	—	Dev. D-2	—	—	—	38	—	65	23,184	—	
	1949	8	8	42 †	Dev. D-3	5,950	375	40%	39	2·39	920	1,628,883	108,360,000	
	1951	—	—	—	L. Cret.	4,630	—	—	35	—	—	—	—	
Heart's Hill (Sask)	1950	—	—	—	L. Cret.	2,685	10	—	14	—	—	—	—	
Joseph Lake	1949	77	82	82 †	Viking (Cret.)	3,300	12	45%	37	2·25	40	1,524,833	16,200,000	
Jumping Pound	1944	5	6	—	Mississ.	10,000	—	—	Dist.	—	—	116,919	—	
Lea Park	1951	—	2	—	L. Cret.	1,500	—	—	14	—	G.F.P.	401	—	
Leduc Woodbend	1947	474	495	692 †	Dev. D-2	5,000	30	30%	39	—	41	14,834,618	70,950,000	
	1947	454	458	472 †	Dev. D-3	5,300	34	50%	39	2·47	78	33,172,825	194,250,000	
	1950	23	26	?	L. Cret.	4,195	—	?	35	—	45	821,079	?	
Lloydminster (Alta. & Sask)	1939	384	—	—	Cret.	1,900	20	—	9–18	1·40 •	45	9,332,193	—	
Majeau Lake	1951	—	1	—	Mississ.	4,250	85	—	Wet Gas	—	—	—	—	
Neapolis (Olds)	1951	—	1	—	Dev. D-3	8,110	20	—	60 Wet Gas 58	—	—	4,049	—	
New Norway	1951	10	10	—	Dev. D-2	4,660	100	—	38	1·91	72	117,440	—	
		6	6	—	Dev. D-3	4,870	60	—	—	—	41	59,195	—	
Normandville	1949	1	1	—	Dev. D-3	6,700	30	—	39	—	—	7,112	—	
Norman Wells (N.W.T.)	1920	—	—	—	Dev. D-3	1,500	425	—	38	—	—	—	—	
Okotoks	1951	—	3	—	Dev.	8,686	—	—	Wet Gas	—	—	—	—	
Pincher Creek	1948	—	2	?	Madison	12,000	394 †	—	52·5	—	—	—	—	
Pine Lake	1951	1	1	—	Dev. D-2	7,050	—	—	—	2·99 •	—	29,288	26,000,000	
										Calgary				
Princess Brooks	1939				Cret.	3,250	12	—	—	1·08 •	—	—		
	1942	9	14	—	Mississ.	3,310	12	—	25–33	—	—	913,349	—	
	1944				Dev. D-2	3,975	32	—	—	2·01	—	—		
Redwater	1948	909	922	925 †	Dev. D-3	3,200	98 †	50%	33–36	2·31	97	51,444,703	700,000,000	
Skaro	1951	1	2	—	Fragmental	3,680	—	—	37	—	—	2,498	—	
South Calmar	1951	8	8	—	Dev. D-3	6,190	15	—	40	2·51 •	131	174,931	—	
Glen Park		1	1	—	Dev. D-2	—	—	—	—	—	43	1,556	—	
Spotted Lake	1951	—	—	—	Dev. D-3	5,667	—	—	—	—	—	—	—	
Spring Coulee Del Bonita	1950	14	14	—	Madison	6,000	—	—	36–49	2·44	G.F.P.	120,509	—	
Stettler	1949	2	2	—	L. Cret.	4,100	—	—	28	—	39	43,664	—	
		39	40	100 †	Dev. D-2	5,100	58 †	30%	31	—	41	756,938	18,400,000	
		20	20	25 †	Dev. D-3	5,400	26 †	40%	31	1·40 •	42	358,919	3,840,000	
Taber Conrad	1942				Cret.	3,000–3,200	35	—	18–23	1·63 •	G.F.P.	2,775,097	—	
	1944	25	38	—	Jurassic	3,100	10	—	26	—	G.F.P.	—	—	
Turner Valley	1914	2	3	—	Cret.	2,500	15	—	—	—	—	—	—	
	1924				Mississ.	4,000–6,000	106	—	35–39	2·79 •	—	—	—	
	1936	262	326	326	Mississ.	6,000–9,600	146	—	—	3·41 •	G.F.P.	111,205,398	127,000,000	
Virden (Man)	1951	—	—	—	Mississ.	2,330	—	—	33	—	—	—	—	
Whitelaw	1950	—	1	—	Perma Penn.	3,815	250	—	28	1·01 •	—	9,829	—	
Whitemud	1949	4	4	—	L. Cret.	4,000	—	—	35–39	2·66 •	39	108,477	—	
Wizard Lake	1951	—	—	—	L. Cret.	4,870	35	—	—	—	—	—	—	
					Dev. D-2	5,695	30	—	38	—	—	—	—	
		22	22	22 †	Dev. D-3	6,300	342 †	—	—	2·48	250	941,123	50,800,000	

• Indicates F.O.B. G.F.P. Good field practice. † Based on reserve calculations to 1.10.51 by A. I. Levorsen.[14, 15]



(AFTER ALBERTA DEP OF MINES AND MINERALS)

FIG 3

STATISTICAL DATA OF ALBERTA OIL INDUSTRY

the Western U.S. is now approved, and export to Eastern Canada is likely to follow soon. This will allow the development of gas fields in the Peace River area, Southern Alberta, and Saskatchewan, and will even stimulate further search for gas.

Areas of Activity

Exploration developments in Western Canada are reviewed every June in the *Bulletin of the American Association of Petroleum Geologists*, and these articles form a good source of information.

Fig 4 (after A. J. Goodman [5]) shows the most important discoveries to date. Present activities may be summarized as follows :—

Foot-hills Belt

Surface mapping and geophysical surveys are going on in preparation for further testing in this complicated belt, which requires drilling to 10,000 to 12,000 ft. Large reservations are required in view of the high costs and risks. The eastern rim of the area (through Barons and Olds) is not complicated by thrusting and is being tested by some 8000- to 10,000-ft wells.

Fort St John Area

This area is currently being actively tested by drilling in efforts to establish wet gas reserves. The belt to the west is almost entirely under reservation, and is being investigated.

Peace River Area (around Normandville on Fig 4)

Drilling and geophysical work on large reservations are going on in order to evaluate gas reserves for export in the near future. No major oil discoveries have been made to date, but a recent discovery at Sturgeon Lake shows promise.

Northwest Territories

In the early part of 1952 a land rush in the Fort Simpson Land Block resulted in permits for over 16,000,000 acres being taken out. Shallow Devonian prospects are anticipated.

Alberta—Southern Plains

In the western belt from Acheson to Drumheller, detailed geophysical re-surveys and drilling are intense and devoted to the discovery of Devonian reefs. In the eastern belt drilling is less intense, and Cretaceous gas and medium oil are the objectives.

Southern Saskatchewan

There has been a great increase in exploration activity in this area, and several promising discoveries have been made recently. Thirty-three rigs are currently engaged in exploration drilling. Recent discoveries include promising extensions in the Coleville heavy oil area, medium oil at Fosterton and Eastend, and light oil at Ratcliffe. These isolated discoveries are being evaluated, and full development must await improved oil marketing conditions and transportation facilities.

Manitoba

The southwest corner of Manitoba is now being more energetically explored, and light oil discoveries at Virden, Linklater, and Tilston show promise.

Availability of Information

The greatest single source of information concerning wells is the Conservation Board. The Board defines areas of exploitation, and within the boundaries of these areas all information concerning each well is available, theoretically, a week after that information is obtained. This will include electrologs, core analysis, oil and gas shows, well samples, drill stem tests, and all pertinent drilling and completion data. The financing of the maintenance of these records is made through the medium of the Oil and Gas Conservation Tax, but any person can examine the records by payment on a certain fixed scale of charges for each item of information.

In the case of wells outside these boundaries, the information is not released by the Conservation Board until one year after the completion of the well.

Alberta legislation relating to petroleum can be obtained from the Minister of Mines and Mineral Resources.

For persons entering the western oil picture, maps can be obtained from the Conservation Board covering almost any area of development in Alberta, but there are also map service companies which provide both lease and land maps, electrologs, and a variety of compilations of all provinces. Geological maps and reports should be obtained from the Geological Survey Division of the Department of Mines, Ottawa.

Useful daily and weekly news sheets are published such as, the *Daily Oil Bulletin*, *Myers Oil News*, *Oil in Canada*, and *The Western Examiner*. The Conservation Board puts out a weekly Bulletin listing all locations and the status of wells and a monthly publication giving certain production statistics. A regular directive is issued setting up the " allowables " for the ensuing month. Each year, the Board publishes a " Schedule of Wells," summarizing well data that has been released up to the year-end.

The Western Canada Petroleum Association is a most active body and a source of much general information. A statistical department has been set up recently.

The various banking houses are competitive, and issue regular brochures and monographs on the oil business. The investment houses have naturally taken an intimate interest in the oil business, and a new-comer is recommended to acquire one of the several directories which give a good analysis of almost every operating company.

Except by exchange of information and through the medium of the " Scout Check " only limited up-to-date wildcat or geophysical information can be obtained. The " Scout Check " is an Association of some thirty companies, who each supply one man who is allocated an area to scout information, all of which is pooled and exchanged at a weekly meeting. In order to qualify for entry into the Scout Check, a company must be engaged upon a certain minimum amount of development work and have acquired some acreage.

Apart from a relatively small amount of work done by themselves, the Government does not publish any geophysical results, although they demand a statement of expenditure and the results of any geophysics done on every reservation or lease.

Production : Maximum Permissible Rates [16]

" Maximum permissible rate " (MPR) is the term used by the Conservation Board in Alberta to define the average maximum daily rate at which wells might be permitted to produce. The MPR is based on the idea that a hypothetical reference well with an assigned productive area of 40 acres, a producing zone T ft thick, porosity of 10 per cent, connate water of 25 per cent, a shrinkage factor of 75 per cent, and an expected recovery of 20 per cent over a ten-year life, will have an average daily production of approximately T brl. Since the representative well is assumed to be in a fully developed field, early development wells may have their MPR increased to an imposed maximum of $2\frac{1}{2}T$, and this is progressively decreased as more wells are drilled. The representative MPR may be modified by penalty or bonus factors for deviations from normal in such properties as reservoir pressure, gas : oil ratio, water : oil ratio, and assigned acreage. In a large pool such as the Leduc D-2 reservoir, these modifications apply only to the fluid-ratio corrections (penalties). Variations in zone thickness within the same reservoir are ignored, as they would cause too many complications.

The MPR represents the maximum rate allowed in a field, but all fields are not allowed to produce at this maximum, since market proration is also applied. The plan adopted by the Conservation Board involves a minimum " living wage " or " economic allowable " for all wells, based primarily on well depth. The surplus between the market requirement and the sum of all the economic allowables is then prorated among these pools whose MPR are in excess of their economic allowables. The pool allowable thus set is then used to determine a minimum daily allowable for each well in the pool, having regard for sub-normal wells that are unable to produce their quotas due to penalties or defects.

The system outlined enables production to be regulated to conform to market requirements, and at the same time achieves a fair distribution. At present production is restricted by shortage of pipeline accommodation, but it is anticipated that by the time the Edmonton–Vancouver pipeline is open, that the increased number of producing wells will result in little, if any, increase in daily allowables. In any event, the increase will go to the wells having the highest MPR, notably the D-3 reef producers.

Inspection of Table I shows that many fields producing from 5000 ft are allowed only 40 to 50 b.d. The producing life of these fields may be extensive, but the rate of capital return is, in general, disappointingly low.

Information Concerning Leases and Reservations with Respect to Oil and Gas Exploration and Development

Introduction

Crown lands are subject to different regulations according to whether they are provincial or federal. Regulations also differ in each of the four

Western Provinces. In general, regulations in Alberta are more specific, and relate better to present conditions due to the relatively maturer state of oil development in that Province. Regulations in Saskatchewan are being modernized, and are essentially based on the Alberta regulations, with some differences. Rules in British Columbia and Manitoba will very likely be modified as the industry develops.

Revenue to the Province follows the pattern of low return during the period of exploration and higher revenue once commercial oil has been discovered. The higher revenue is partly derived from royalties and partly from cash bonuses derived from the sale of proven and semi-proven acreage.

Freehold mineral rights are essentially controlled by the Hudson's Bay Company, the railway companies, and by individual owners, of which only the two latter sources are available for development. General terms and conditions are similar in the different provinces, subject to wide variations due to quality and demand.

Distribution of Mineral Rights

Alberta

The Province of Alberta contains 163,000,000 acres, of which nearly 150,000,000 acres is potentially oil-bearing. The minerals in almost 16,000,000 acres have been patented and are freehold. The freehold land can be subdivided as follows :—

Railway grants	13,031,731 acres
Hudson's Bay Company	2,404,000 acres
Individuals and other companies	564,269 acres

The Provincial Government controls the mineral rights over 132,620,000 acres, and disposes of these through the Department of Mines and Minerals at Edmonton. Up to 31 August 1952, the following distribution had been made [6] :—

742 reservations issued comprising	44,537,716 acres
18,189 leases issued comprising	12,158,268 acres

Up to 31 December 1951, 8,250,000 acres of C.P.R. lands were under license.

Saskatchewan

The Province of Saskatchewan contains 161,088,000 acres, of which about 75,000,000 acres are potentially oil-bearing. The land can be subdivided as follows :—

Freehold mineral rights	24,000,000 acres approximately
Made up by :—	
Railway Grants	
Original grant	15,000,000 acres
Now held	6,600,000 acres
Hudson's Bay Company	
Original grant	9,000,000 acres
Now held	2,352,886 acres
Individuals	15,000,000 acres approximately

The following mineral rights are under reservation or lease :—

Provincial lands (up to 18 September 1952)	
290 Permits issued comprising	34,400,083 acres
723 Leases issued comprising	1,132,213 acres
C.P.R. lands (up to 31 December 1952)	
Under licence	2,800,000 acres
Under lease	Small area based on 160 acres per well drilled

It is estimated that a total of 64,000,000 acres is being actively explored.

Manitoba

Manitoba contains 157,767,680 acres of which approximately 20,000,000 acres are potentially oil-bearing.

On Provincial lands	
46 Reservations issued comprising	4,283,090 acres
35 Leases issued comprising	12,544 acres
On C.P.R. lands licences have been issued over	270,000 acres

British Columbia

British Columbia contains 227,747,200 acres, but for the present discussion only approximately 50,000,000 acres, in the belt east of the Rocky Mountains, are considered to be potentially oil-bearing. It appears that the mineral rights involved are almost exclusively under provincial and federal control.

Up to 6 September 1952, the distribution of Provincial rights was as follows :—

479 permits issued comprising	32,043,722 acres
102 permit applications and pending issue in the near future comprising	3,717,524 acres
48 licences issued comprising	485,425 acres
18 licences approved and pending issue comprising	206,080 acres
24 leases under Coal and Petroleum Act of 1936 are in good standing and include	12,565 acres

At the present time permits cover the belt that can be conservatively considered to be potential oil land, except for less accessible land in the north.

Northwest Territories and Yukon

This contains up to 130,000,000 acres of potentially oil-bearing land. Over 16,000,000 acres have been taken under permit in Northwest Territories. The more remote areas await investigation at a later date.

Reservations and Leases in Alberta [7-10]

Reservations

Provincial lands are first issued in the form of reservations, which correspond to a low rental prospecting permit. The following system has operated since 1947. A company or individual may acquire and hold not more than two reservations at any time, each comprising not more than 100,000 acres. Large companies commonly hold additional reservations through subsidiary companies.

The following procedure applies only when land is first placed under reservation. The applicant applies for a block of land, which is assumed

to be available, and pays a fee of $250 per reservation and deposits $2500 for each part of 20,000 acres, as a guarantee that his obligations will be fulfilled.

The Alberta Department of Mines and Minerals checks that the application is in order and if so issues a permit. The permit holder must file a plan of exploration within ninety days. " Exploration " may take any form which has an application to the geological or geophysical investigation of the permit. If the plan is approved, evidence must be submitted of the engagement of trained personnel for conducting the work, which must be undertaken within a reasonable time, bearing in mind weather and climatic conditions. The permit is periodically renewed conditionally over three periods of four months (rent free), two three-month periods at 7 cents per acre, two more at 8 cents per acre, and four more at 10, 15, 20, and 25 cents per acre respectively. Renewal is not allowed after the second 8-cent period unless continuous drilling has commenced—" continuous " is interpreted as allowing not more than three months between the abandonment of one well and the starting of the next. If oil is discovered leases must be taken in the vicinity of the well within three months or before drilling another well within 4½ miles of the discovery. The balance of the reservation may then run its normal course as a reservation. The investigations listed above may be performed progressively, since continuous activity can be insisted on by the Province. For this reason low price reconnaissance surveys are sometimes undertaken first and followed later by detailed local seismic surveys. The permit-holder has the option of discarding the permit or of drilling before taking to lease or of taking to lease. The more information that can be obtained before taking to lease the better the leases may be selected.

Leases

On taking to lease, not more than 50 per cent of the lands in any individual township may be retained. The maximum individual lease blocks permitted are squares of 3 miles by 3 miles or rectangles of 4 miles by 2 miles and the minimum unit is the quarter-section or 160 acres. The length shall not exceed twice the width.

If lease tracts do not corner, a corridor of 1 mile must be left free. Leases may also be selected in a draughts-board pattern.

The term of the lease is twenty-one years, renewable for similar periods so long as oil or natural gas are produced. Rental is $1 per acre per year. The residual portions of the reservation after taking to lease are reserved by the Province as Crown Reserves (C.R. Parcels) and are subsequently available for leasing at public auction by sealed bids, and any person, including the holder of the original reservation, may tender a bid.

Half of the approved expenditure during the reservation may be credited against the first year's rent, but rentals do not go in aid of royalties.

Royalties

Crude Oil.—Royalty is exacted on a sliding scale, ranging from 5 per cent on production up to 600 brl per month and increasing to 16⅔ per cent on production above and including 4050 brl per month.

Natural Gas (if " dry " or " residual " after processing).—Royalty is

15 per cent of selling price or fair market price at the place of production, provided this is not less than ¾ cent per 1000 cu. ft.

Fluid Hydrocarbons and Sulphur Recovered from Wet Gas.—Royalty is 12½ per cent of fair value of products.

Special Provisions Concerning Gas Licences and Leases.—Since January 1951 special provisions encourage the development of gas leases. The standard spacing for gas wells is 1 square mile, and hence the configuration of some leases intended for oil-well spacing is not suitable for gas development. If gas is discovered on a reservation in a certain zone or zones a gas licence may be obtained for a rent of 5 cents per acre every six months for a term up to three years. During this period the holder must undertake " continuous " drilling as already defined, and at any time within the three years may take out gas leases for any part or all of the reservation. The extent of the leases that can be obtained is determined by the drilling done, and each completed gas well down to depth limits of 3000, 6000, and in excess of 6000 ft enables area of six, eight, and ten sections respectively to be leased around the well. Rental on gas leases is 10 cents per acre per year until a market is available, and then at a rate that will be determined by the Lieutenant-Governor-in-Council.

Provincial Land Sales

This general term is applied to the issue of provincial leases and reservations by the three following methods :—

(i) Provincial Crown Reserve Sales.
(ii) Provincial Crown Reservation Sales.
(iii) Provincial Mining Recorder Sales.

Provincial Crown Reserves Sales deal first with the portions of reservations that revert to the Province after the reservations have been taken to lease, and secondly with other small parcels on which the Province holds the mineral rights. Companies or individuals request the province to offer such parcels of land for sealed bid. Parcels range from one section to one or more well sites, and one-quarter and one-half section are the most common areas offered.

Bids must consist of a cash bonus, sometimes, but rarely, accompanied by the offer of an additional royalty and by advance rentals for one year plus registration fees. The money is returned when bids are unsuccessful. The bids are appraised by qualified government technicians, and if all bids received on a particular parcel are deemed too low the bids are rejected. The descriptions of the acreage offered are published well in advance of the date of the sale, and seismic investigation by any interested party is possible. The leases vary in quality from proven and semi-proven to rank wildcat acreage, but under this highly competitive system reasonably proven " light oil " land sells for about 50 cents per barrel of reserves. To date the record price is $3,110,000 for one quarter-section in the Bonnie Glen area. One quarter-section in the Golden Spike area was sold in 1950 for $1,500,000 plus an additional royalty of 15 per cent and proved to be " dry," thus illustrating the hazards involved in the evaluation of semi-proven land. High class unproven acreage occasionally sells for $100,000 to $200,000 per ¼ square mile, when seismic and sub-surface investigations

favour the chances of a D-3 reef being present. Average prices for *unproven* acreage between November 1950 and August 1952, have varied from $71 to $218 per acre and averaged about $125.

Provincial Crown Reservation Sales.—New reservations in Alberta are available only in inaccessible or poorly prospective areas; consequently, older reservations are at a premium. From time to time reservations are returned to the Province, either because exploration obligations have not been fulfilled, or because the permit holder decided to drop the acreage. Such returned reservations are offered for bid by sealed tender under similar conditions to those of the Reserve Sales. The rentals and conditions for the re-issued reservation are the same as those for normal reservations, apart from the cash bonus. Cash bonuses are low, ranging from a few cents to a dollar or so per acre as a rule. If no bids are received for any unsurveyed tract, it may be issued to the first representative to apply to the District Mining Recorder office on the day after the sale, subject to fees of a year's rental and registration dues.

Provincial Mining Recorder Sales.—These sales involve provincial lands consisting of small parcels and larger blocks, but less than reservation size, that have been returned to the Province by default of rents or obligations. Sale is by sealed tender with cash bonus. The smallest unit involved is a quarter-section, and while tenders may be made for larger blocks, each bid is regarded as so much per quarter-section, thus a tender may be successful over only part of the area on which the bid was made. The tenders and fees must be presented by personal representation and, immediately after the dead-line bids are analysed and results announced, each successful tenderer must select, within an hour or two, half of the acreage which it is desired to retain. The remaining half reverts to the Province. The selected leases must conform to the dimensions imposed on leases. Any tracts which are not bid for may be issued without cash bonus for normal rental and registration fees to the first representative to make application for it the next day. Cash bonuses for recorder tracts are usually very low —from a few cents to a dollar per acre.

Reservations and Leases in Saskatchewan

Regulations concerning these are laid down under the Oil and Gas Wells Act (8 June 1951) which consolidates regulations relating to petroleum and natural gas contained in the Mineral Resources Act. See also [10] for a summary on which the following account is based.

Exploratory Permits

These are equivalent to "reservations" in the Alberta regulations Applications may be made for areas up to 100,000 acres (to the Director of Mineral Resources, Department of Natural Resources, Regina) and must be accompanied by a plan, a description of the land, programme of proposed work, statement of ability to have work done, and rental for first year. The rental will be returned if the application is rejected.

Term of Permit.—The term of permit is three years from date of issue. No extension or renewal is granted.

Rentals.—Advance rentals are due annually at respective rates, for first, second, and third years of 2 cents, 5 cents, and 10 cents per acre.

Operation.—" Operation," *i.e.*, investigation, must be begun within ninety days of commencement of term and diligently carried on. Permittee must expend money as follows :—

First year : On investigation—20 cents per acre or $10,000, whichever is greater.

On drilling—no requirement.

Second year : On investigation—40 cents per acre. Of this expenditure at least one-half or $15,000, whichever is greater, shall be spent on drilling.

Third year : On investigation—60 cents per acre. Of this expenditure at least one-half or $15,000, whichever is greater, shall be spent on drilling.

Surrender.—Any or all of the permit may be surrendered at the end of any permit year, subject to thirty days' notice in writing. Six months after the end of each year a detailed statement must be furnished to the Provincial Government giving full particulars of geological and geophysical work and expenditure. Release of information by the operator may be waived until six months after expiry of the permit if $10,000 is deposited.

Information to be Furnished.—Information furnished will not be released to the public until three years after expiration of the permit or withdrawal of any lands.

Expenditure.—Excess expenditures in one year may be credited against a maximum of half the required expenditure of the next year.

Petroleum in Commercial Quantities.—If the Provincial Government considers that a well has established petroleum in commercial quantities, the permittee is notified and required to take a lease of not less than 1200 acres surrounding the well.

Leases from Permits.—Leases within a permit may be issued as applied for. The permittee has the exclusive right to obtain leases within the permit area both during the period of the permit and within sixty days of expiry of the permit, unless default occurs.

Rental Credits.— If the permittee has fulfilled all requirements, excess expenditures may be credited against first year rentals.

Leases

Leases may be issued over Provincial lands which have or have not already been included in permits. The application shall be accompanied by a plan and rental due up to 1 April at 5 cents per acre.

Lease tracts must be rectangular and no side longer than 3½ miles. Unless adjacent tracts have a common corner, corridors of at least 1 mile are required. The proportion of Provincial land permitted to be leased in any township varies according to the size of the tract :—

if no side exceeds 2 miles up to 60 per cent may be leased; if two sides exceed 2 miles, but are less than 3 miles, up to 50 per cent may be leased, and if two sides exceed 3 miles, but do not exceed 3½ miles, up to 40 per cent may be leased. Lease tracts must not be less than 40 acres and not more than 23,040 acres.

Term of Lease.—Term is twenty-one years, subject to renewal for a further like term if there is no default.

Rental.—Rental is $1 per acre per year, payable in advance. For the first three years of a lease, expenditure on actual drilling (exclusive of cost of machinery and casing) may be credited against rentals.

Drilling.—Notice may be given by the Province at any time requiring drilling to commence on a lease within six months. A Government licence is required for drilling operations and a deposit of $5000 per well must be made.

Offset Wells.—If the leased lands adjoin privately owned mineral lands in which petroleum in paying quantities has been discovered, the lessee shall, on written request from Government : (*a*) offset the well or wells by a like number of wells, (*b*) pay royalty to the Government according to the production of the private wells, or (*c*) surrender to the Government the legal subdivisions offsetting the private wells.

Grouping of Leases.—For purposes of drilling obligation and expenditure small leases may be grouped in units not exceeding 23,040 acres, provided individual blocks are not separated by more than 2 miles.

General Conditions Applying.—(1) Operators must comply with Mineral Resources Act and Oil and Gas Wells Act, the terms of which reflect normal oilfield practice. (2) Accurate records of operations and expenditures are required. (3) All assignments must be approved by Government. (4) Permits or leases are granted only to corporations or partnerships that comply with laws concerning registration of such bodies.

Surface Rights.—Permits and leases do not authorize use of the surface. The operator may agree with the surface owner privately on the compensation to be paid. The regulations contain detailed instructions on how such compensation should be estimated. Geophysical surveys can be run along road allowances without infringement of surface rights. If it is impossible to agree on compensation, the operator may apply to the Government and a speedy decision will be made by the Arbitration Board which considers such cases.

Royalties.—Royalties on all liquid hydrocarbons vary according to the monthly production of the individual wells, as follows :—

Lower limit—900 brl or less	5 per cent
Over 6000 brl per month	15 per cent

Gas royalty is 5 per cent of the value, but not less than $\frac{1}{2}$ per cent per 1000 cu. ft.

Crown Reserves.—An area equal to 25 per cent of the total Crown lands in any permit or Crown lease is set aside as a Crown Reserve. Thus if an application is made for a permit over 100,000 acres of Crown lands the boundaries will include 100,000 acres plus a reserve of 33,333 acres. The 33,333 acres is selected in single, isolated sections throughout the leases or permit.

Crown Sales

An approximately similar system to that in use in Alberta is in force in Saskatchewan. Reservations and leases available for sale are advertised, and any interested organizations may receive lists of forthcoming sales on application to The Director of Mineral Resources, Department of National Resources, Regina, Saskatchewan. Reservations are currently offered for

free application, subject to rental and legal fees, but if more than one application is received the reservation is re-offered for bid by sealed tender. Leases are also offered for sealed bid.

Conservation Board

A Conservation Board has recently been established in Saskatchewan by the Oil and Gas Conservation Act, 1952, and the final draft of the Act will soon be issued. Regulations will be very similar to those in force in Alberta.

Permits and Leases in Manitoba

These are regulated by the Department of Mines and Mineral Resources under the Mines Act of 1940.

Reservations

Reservations are classified as "geological and geophysical" and "drilling."

Geological and Geophysical Reservations.—These range from 200,000 to 10,000 acres in extent. Within thirty days a programme of work by qualified personnel must be submitted. Sixty days is allowed if subsurface work is contemplated. The fee is $250 plus a cash deposit of $750 for surface work and $2000 for subsurface work for each 20,000 acres or portion thereof in the reservation. If application is made between 1 October and 31 March, the effective date of issue of the reservation is 1 April. Work is not required during the winter months. The normal term for a reservation is twelve months. Renewal for a further twelve months at monthly intervals is allowed, subject to approval. Extension for a further period up to six months is possible on payment of 5 cents per acre. Such a reservation is rent-free. An alternative, more onerous, type of agreement allows a three-year term with the following conditions: an additional fee of ½ cent per acre, an additional cash deposit of 5 cents per acre, and a deposit of a bond for at least 25 cents per acre as a guarantee that 30 cents per acre will be expended on work during the three years. The holder of a reservation may terminate it at any time, provided he has made the prescribed expenditure, and that he furnishes full information on all work performed, or he may take to lease up to 50 per cent of the reservation. The term of the lease will be computed from the date on which the reservation became effective.

If drilling is undertaken on this type of reservation the quarter-section on which the well is drilled must be leased. The act of drilling will validate the rest of the reservation during the continuation of the exploration by drilling.

Drilling Reservations.—An application must be accompanied by a fee of $250 and a cash deposit of $1 per acre. The area of reservation shall not exceed 10,000 acres, and the length shall not be greater than twice the breadth. Within thirty days of application, proof must be given of engagement of qualified personnel and information as to the date on which operations will commence. A report of the geology of the area, compiled from existing sources, must be submitted. Commencement of work during the winter months is not required. An additional licence is needed if it is

wished to make a geophysical survey. The term of a drilling reservation is sixty days from the effective date of issue, but may be renewed for successive sixty-day periods up to one year, provided satisfactory progress is made or that delay is beyond the control of the operator. If default occurs renewal is still possible subject to a penalty to be assessed by the Director. Drilling equipment should be installed within the first sixty days and drilling be started with reasonable diligence. If oil or gas is found in commercial quantity the reservation shall terminate, and the holder shall have the right to apply for leases over any part of the reservation. If the well is abandoned the holder has the choice of : (*a*) taking to lease, (*b*) terminating the reservation, or (*c*) keeping the reservation in good standing by drilling a further well within sixty days. The holder may establish a credit in his favour by his exploratory examination of the reservation, and up to 75 per cent of this credit may be applied to first-year rentals of any leases that are taken out.

Drilling Reservations have not been found suitable by the industry, and in fact none have been issued, since the geophysical investigation of the larger areas offered by Geological and Geophysical Reservations has been preferred.

Leases

General Conditions.—The primary term of a Manitoba Provincial lease is three years at 50 cents per acre per year rental, and the secondary term is six years at an annual rental of $1.50 per acre. If oil or gas production are obtained within either of the terms the yearly rental is 50 cents per acre, and the lease may be renewed for successive six-year terms as long as there is commercial production. The area of a single lease shall not exceed three sections and shall not be less than a quarter-section. The total extent of all the leases acquired by an operator—except by assignment—during any one year shall not exceed fifteen sections. Leases carry a one-year drilling obligation, but this may be waived at the discretion of the Director. Subsequent drilling obligations fall due six months after the completion or the abandonment of the first or subsequent wells. Offset drilling is required when oil is discovered in paying quantities adjacent to a lease. Credit established by drilling, up to 75 per cent of the expenditure, may be applied to the first-year rental of any lease within 25 miles of the well. If the credit is in excess of this amount, it may be applied at the discretion of the director for rentals up to three years. No credits are allowed for operations within $\frac{5}{8}$ mile of a commercial oil or gas well.

Royalties.—Oil royalty in Manitoba is 12½ per cent of the value of the oil. Gas royalty is 12½ per cent of the selling price or fair value, provided it is not less than ¼ cent per 1000 cu. ft.

Reservations and Leases in British Columbia

A compact review of the Petroleum and Natural Gas Act (Amended 1950) is available by G. W. Auxier.[11]

Permits

A company may acquire the right to prospect by surface geology only, by obtaining a permit for an area up to 256,000 acres for a fee of $250 plus

a rental of $500 for each 10,000 acres. This may be renewed twice for one year each time at 10 and 20 cents per acre respectively, and in special circumstances two further renewals of six months at 20 cents per acre are permitted. The applicant must state the type, extent, and approximate cost of the proposed prospecting and the estimated duration. If, during the first year, work equivalent to the amount of rent paid is done or if a licence is obtained, the Minister may refund the first year's rent.

If geophysical work is required, a special licence is needed, costing $25 per year and a deposit of $1000.

Licences

If the permittee complies with permit terms, he has the exclusive right to a licence or licences covering apparently all or any part of the permit area. A single licence may range between 320 and 11,520 acres, and must be of prescribed shape.

If a licence is desired in the first instance, it can be obtained without taking out a permit. The licence gives the right to search, to prospect, and to conduct drilling operations, and the licensee must indicate the type, extent, cost, and duration of the work.

Licences cost $25 plus 25 cents per acre yearly rental, and may be renewed from year to year at the same fee and rental. At any time the Minister may absolve the licensee from further development if the market conditions do not warrant, and the licence may be held on payment of rentals and fees.

If the licensee expends over $7.50 per acre in drilling, he may apply for a credit, which may be applied during the ensuing three years on any permits, licences, or leases.

Leases

General Conditions.—If, and only if, the licensee finds oil and gas in commercial quantities on the licensed area, he may apply for a lease, and indeed he may be compelled to do so within ninety days of securing production. The leased area must not exceed 50 per cent of the licensed area, and the maximum dimensions are 3 miles by 3 miles if square and 2 miles by 4 miles if rectangular. Leases can touch only at the corners, otherwise a corridor 1 mile wide must be left on all sides as a Crown Reserve. The lease fee is $25 and yearly rental $1 per acre.

The term of the lease is twenty-one years, subject to renewal. If a gas field is found and reasonably delimited, rental is reduced to 50 cents per acre and, if no adequate market is available, to 25 cents per acre.

Grouping of Leases or Licenses.—Leases and licences may be unitized in "groups" of up to eight "locations" or tracts for development of oil (more than eight for gas). The licences or leases so grouped must not be split, but the tracts of more than one operator may be grouped around a community well. Leases may be taken anywhere within the group, subject to the rules concerning size and shape.

Reserves.—The Lieutenant-Governor-in-Council may declare any area not already under permit to be a "reserve." Lands may still be licensed therein, but for each licence an adjacent area of equal dimensions to that licensed becomes automatically a "Crown Reserve." Crown Reserves

may be disposed of by tender, but when adjacent reserves are formed as described above, the licensee has the right to bid it successfully at 90 per cent of any acceptable tender made by any other party. The development of British Columbia leases is still at an early stage, and a sale by tender of Crown Reserves has not yet taken place.

Royalties.—Royalty for oil is 12½ per cent and for gas is 15 per cent of gross value with a minimum of ¾ cent per 1000 cu. ft.

Surface Rights.—Four weeks' notice is required to private owners, with a deposit to guarantee against loss or damage. The operator has an automatic right to use land, where the Crown owns the surface rights, as may be necessary.

Staking.—In unsurveyed territory leases and licences must be staked before application is made. This is not necessary for geophysical permits, when a signed and dated map will suffice, in which the permit area may be described by reference to some feature recognizable on Departmental reference maps.

Permits in Northwest Territories and Yukon

Exploration Permits are issued by the Federal Government with a maximum of 64,000 acres in one block with a limit of eight permits to a company. Five cents an acre must be spent in exploration during the first eighteen months, 25 cents an acre in the next year, and 30 cents an acre in the following year. Thirty-five per cent of the acreage in a permit may be taken to lease for a yearly rental of $1 per year.

During the first half of 1952 some 16,000,000 acres were taken under permits in the Fort Simpson Land block, immediately north of the Alberta border.

Freehold Leases (All Western Provinces)

General Conditions

Freehold leases involving petroleum and natural gas follow a similar form throughout the four western provinces. The usual term of lease formerly extended for ten years with extension for as long as commercial production lasted—provided that production was proved in the original term. Under present more competitive conditions, in Alberta, terms are now generally for two, three, or five years on a basis of bargaining with an extension for as long as commercial production can be obtained. Longer terms generally apply in Manitoba and Saskatchewan.

Cash Bonuses

These vary greatly from 25 cents an acre in Manitoba and Saskatchewan to extremes of $1000 or more in semi-proven tracts if the mineral owner has held out until the land is semi-proven.

Annual Rental

Rentals range from $1 per acre for most of Alberta to fractions of this value in Saskatchewan and Manitoba.

Royalty

Royalty is normally 12½ per cent, but in special cases, where the owner has held out, he may receive an additional over-ride and a reduced cash

bonus. Generally speaking, the cash is more attractive, but royalties in wells with large reserves have a high cash value and are the subject of speculation. Additional over-rides are offered only when it is reasonably sure that the wells are likely to find large reserves.

Offset Clauses

These usually require the lessee to offset commercial production in an adjacent lease within 90 or 120 days, depending on the type of lease form used, and " orderly development " within the lease must continue at intervals ranging from 90 to 180 days after the preceding wells have established commercial production. Commercial production is defined as production that justifies the drilling of another well.

Safeguards

Safeguards are contained in the lease form against availability of casing and drilling equipment, strikes, and adverse weather conditions.

Canadian Pacific Railway Lands

As one of the conditions of construction of the railway, the Canadian Government granted to the C.P.R. all of the odd numbered sections except Sections 11 and 29 in each township for a distance of 25 miles on each side of the main line of the railway. Exchanges have taken place, and the pattern has changed in places.[9]

Until about 1908, settlers purchasing land from the C.P.R. acquired all or some mineral rights, together with the surface rights, but subsequently the mineral rights were excluded.

The C.P.R. have been in the fortunate position of holding substantial draughts-board spreads of mineral rights, and they have leased these to some of the larger companies under terms as follows :—

C.P.R. Reservations

Under present terms C.P.R. Reservation Licences are issued over any available area for $1 per acre, valid for one year. These permit geological and geophysical investigation, but not drilling. Information thus obtained must be furnished to the C.P.R. According to regulations, the licences are not renewable, but at present renewal is permitted if reasonable diligence is shown.

C.P.R. Leases

On completion of surface work in a reservation, if it is desired to drill, a lease may be taken out over 160 acres (640 acres, if gas is expected) and drilling must commence within six months. This act of drilling in part of the reservation allows the licence to be kept in good standing, subject to renewal of rental. If this well is completed as a successful producer, offsets must be drilled within four months, and additional leases may be taken out subject to the drilling commitment stated. If the well is abandoned the lease may be retained for ten years, and the future of the reservation will depend on whether the licensee wishes to do further drilling elsewhere in the licence. Inactivity may lead to cancellation of the licence, at the discretion of the C.P.R.

The foregoing regulations, at present in force, are more onerous than they were in the past, when large companies were able to obtain reservations at much less than $1 annual rental, and there is a good chance that in the near future acreage will be released due to expiry of the old contracts.

Lands under C.P.R. reservation licences at present amount to :

In Alberta	8,250,000 acres
In Saskatchewan	2,800,000 acres
In Manitoba	270,000 acres

Hudson's Bay Company Lands

By its original charter of 1670, the Company grant covered 947,200,000 acres. In 1869 the Government of Canada purchased rights over this area for a small cash payment and an assignment of about 7,000,000 acres.

In Alberta the Hudson's Bay Company lands amounted to one-twentieth of each township, generally all of Section 8 and three-quarters of Section 26, between the U.S. border and the North Saskatchewan River. As a result of exchanges, the Company now owns considerable land north of the river.[9] The holdings of the Hudson's Bay Company are being operated by the Hudson's Bay Oil and Gas Company. Present mineral rights holdings of the original Hudson's Bay lands amount to 1,500,000 acres in Alberta, 2,350,000 acres in Saskatchewan, and 700,000 acres in Manitoba.

Conservation

Conservation regulations have been put into effect and tried by experience in Alberta, and similar regulations are in process of enactment for Saskatchewan. The present discussion will be confined to Albertan regulations, and is based on a useful summary published by the Canadian Bank of Commerce.[10]

The following legislation affects drilling supervision, conservation, taxation, transportation, and rate setting :—

(i) The Oil and Resources Conservation Act, 1 June 1950.
(ii) The Gas Resources Preservation Act, as amended 31 March 1950.
(iii) The Public Utilities Act, as amended 7 July 1949.
(iv) The Pipeline Act, as amended 7 July 1949.
(v) The Oil and Gas Fields Public Utilities Act, 1941.
(vi) Mineral Taxation Act, as amended 31 March 1950.

Copies of the above may be obtained from the Queen's Printer, Parliament Buildings, Edmonton, Alberta, on payment of a nominal fee.

The intent of this legislation is to effect the conservation of the oil and gas resources of the province, to prevent their waste, to regulate drilling and production operations, and to give each owner the opportunity of obtaining his just and equitable share of the production of any pool. The Conservation Regulations insist that all development should be carried on according to the best known engineering practices, thereby preventing waste and showing the greatest ultimate recovery. The Government intend, by way of these Conservation Regulations, to establish prospecting and leasing operations which are designed effectively to prevent monopoly and to encourage individual enterprise. The regulations are designed to

assure to the owners of surface rights fair treatment in awarding compensation for any loss, damage, or inconvenience. Above all, the object of the Government's policy is to assure the orderly development of the oil resources of Alberta for the best interests of the people of the Province and of Canada as a whole.

To carry out these objects, the Board has power to make and enforce regulations covering the spacing of wells, methods of drilling, drilling in water-covered areas, types of drilling tools, casing and materials which may be used for drilling, and the methods of completing the wells, particularly in respect of casing and cementation. They also are entitled to insist upon the taking of samples and tests, the maintenance of proper records, and the regular making of reports to Government on all the operations that the Board has power to make and enforce orders defining field limits. They control and regulate production of wells to ensure efficient recovery, and they can require the extraction of natural gasoline and other substances from any gas produced. They can require the operators to unitize with the object of secondary recovery; and they fix allowables in relation to market demand. In order to ensure that each producer can dispose of his allowable share, the Board has the power to declare that operators of pipelines are common carriers and that the purchasers of oil and gas are common purchasers. In order to protect the owner of the surface rights, the Government has set up a Board of Arbitration which adjudicates between the company requesting a permit from the Conservation Board to drill and the owner of the surface rights in the event of dispute. In the great majority of the cases the oil company and the farmer, whose land is to be drilled upon, come to mutual agreement, and it is seldom that they have to resort to arbitration. Conservation Board officials visit both producing and drilling wells frequently. In the case of the producing wells they insist upon tests which prove the actual production of the well in question. There was a time when one or two wells on a lease would be " over-produced " in order to bolster the production from one or two others which were unable to fulfil their quota. The Conservation Board also conducts routine bottom-hole pressure and echo-meter tests on developed fields in order to assess the rate of decline of the field and to assist the Board in its decision as to the most economical rate of recovery. At the drilling wells the Conservation Board engineers will direct the operator to set adequate casing and will see that proper pressure tests are done on cement jobs. He will also report on any deficiencies of safety equipment such as blowout preventers.

In order to protect the worker the Government has set up a safety board who frequently inspect the drilling operations and can insist upon the operator correcting any deficiency in practice or equipment.

On 31 March 1950 the Government introduced the Gas Resources Preservation Act. The intent was to effect the preservation and conservation of the gas resources of the Province and to provide for their effective use and to prevent waste. To achieve this the Board has the power to grant and renew permits for the export of natural gas. These permits are of limited duration, and will cover only specified quantities of gas. The Board reserves the right to order the diversion of such gas for the use of the consumers of the Province if there is an emergency. When the permit

is issued the terms and conditions are prescribed by the Board setting down the rate at which the gas may be withdrawn and the maximum quantities of withdrawal. Special legislation governing the spacing of gas wells was also introduced at the same time. The difference between the details of this kind as they relate to gas and as they relate to oil should be studied by any person or company wishing to enter into the Western Canadian oil or gas picture. Both the leasing and reservation terms are substantially affected if it is intended to produce gas instead of oil.

In general, the Conservation Board stands to enforce good practices. It is served by an able staff, whose most co-operative spirit enables it to be of great help to the industry.

Company Operations

Classification of Companies

The companies involved in the Western Canada oil picture vary from fully integrated organizations with reserves of over half a billion barrels and refineries with an aggregate throughput of just under a quarter million barrels per day down to a few individuals banded together for the purchase of royalties or farmers' syndicates, prepared either to drill a well or lease a plot of speculative oil acreage. An attempt is made to classify the companies.

Operating Companies of Major Size

These are active in exploration, wildcatting, exploitation, drilling, producing, and in some cases refining, and have two distinct sources :—

(i) Those whose initial operations started in Turner Valley; their revenue from success in that field enabled them to weather the lean years, to continue a modicum of wildcatting, and at the same time pick up cheaply property which has since proved valuable.

(ii) Those who entered the picture, mostly from the U.S.A., after the discovery of Leduc in 1947 and concentrated on the quick acquisition of an acreage spread. Since their entry into the picture they have carried on widespread geophysical work and wildcatting in order to hold the acreage in good standing, and have spent very large sums (up to 20 millions of dollars) before obtaining substantial production.

Operating Companies of Lesser Size

Their activities may be similarly defined, but on a smaller scale :—

(i) Those, whose activities stem from Turner Valley days.

(ii) Those who have grown up from the fact that a person or group of persons held valuable leases in Redwater or Leduc field; generally speaking, these companies are self-supporting.

(iii) Those who, although backed by large interests, have entered from the U.S.A. or elsewhere and, although they entered at an early stage of development, have so far been unsuccessful in locating substantial revenue-earning fields and are compelled to proceed on a small scale.

(iv) Those who have entered a late stage and have picked up secon-

dary interests or farmouts which still have not provided sufficient revenue to make them self-supporting.

(v) Those who were primarily concerned with contract drilling but have now begun to acquire production and interests in acreage in lieu of full payment for drilling contracts. These are probably self-supporting.

Leaseholding Companies of Major Proportions

(i) Those who acquire extensive spreads and plays of acreage over the provinces and then sell out at good profit to new operating companies who wish to start up with a good display of acreage for stock promotion and sales purposes.

(ii) Those who acquire farmers' royalties, particularly in Saskatchewan, with the object of holding them until the present leases expire.

Leaseholding Companies, Syndicates, and Individuals of Smaller Proportions

(i) Farmers having freeholds who group themselves together in order to unitize their acreage sufficiently to justify a request for a drilling obligation.

(ii) Individuals and syndicates, who acquire reservations from Government and sell their interest to late-comers for a bonus, a gross over-ride, or a carried interest.

Service Companies

(i) Cementing, electrologging, diamond coring, petroleum engineering consultants, well-servicing companies, and contract drilling companies are fully represented and strictly competitive. It is quite possible to enter the Western Canada picture on a strictly investment basis and leave all the expert practical work of getting the oil to the service companies. In certain circumstances some of these companies will provide their services free for an interest in the prospect.

(ii) Supply houses exclude the necessity of any stores organization.

(iii) Drafting, map-making, even secretarial, services are available in Edmonton and Calgary. Lawyers have become highly trained in legal drafting of complex oil agreements.

The Financial Resources of Canadian Oil Companies

The volume of capital expenditure in Canada continues unabated, and the largest single contribution to this expansion has been made by the oil industry, particularly in Western Canada. Literally, hundreds of new industries have been established in Edmonton and Calgary, either as a direct or indirect result of the expanding oil and gas development.

As estimated, two hundred American, Canadian, and European companies have injected hundreds of millions of dollars into the broad expansion of all economic activity. Before 1947 about $12 million were being spent annually on oil development, but in 1949 this had risen to $100 million, in 1950 to $150 million, and in 1951 to $200 million.

Production of crude oil in the west has stopped the drain of finance previously required to import crude oil from the U.S. to the Western Provinces, and there has also been a sharp drop in the prices of products to the consumer in the prairies. It is estimated that these two factors

represent U.S. $100 million saved each year and probably about $40 million are being saved by the Prairie consumer.

The Canadian oil industry has received its own capital from many sources. Canadian and American banks, major and minor oil companies, insurance companies, and some of the more conservative Canadian and American investment firms have been involved. But in addition to this, there has been investment through promoters who have not always canalized the money towards the development of oil. The influence of this type of financing should not be exaggerated because it is vociferous.

Earnings, depreciation, depletion funds, and accumulated working capital have not been sufficient to provide for the high volume of expenditure. American companies have been able to use surplus funds from the U.S. which would have otherwise been subject to excess profits tax—the so-called " twenty-cent " dollars.

Large organizations have sold out subsidiary companies in order to finance further development. The success attending the issue of convertible debentures for the financing of the Interprovincial pipeline has led to a series of such issues, all of which have received good public support.

Other companies who have found production borrow on the strength of their oil reserves. A popular form of financing for smaller operators is the " production loan "; on the strength of a geologist's report as to the reserves in a well the banks will advance money for further development of the property.

Finance houses have been prepared to invest in bids for proven Crown acreage, but this form of investment is not now so popular as a result of the slow pay off from small production allowables.

Finally, there is the private financing of ventures by groups of farmers and business men who, either from personal preference or from geological advice, risk their money in drilling or the acquisition of leases and reservations.

Taxation

Prior to 1939, very little had been done by way of tax encouragement for development of oil resources in the Western Provinces. Subsequent to 1939, legislation similar to that existing in the U.S. has been introduced, and the Department of Finances has studied the oil industry and given a good hearing to its problems.*

The present laws may be grouped as follows :—

Exploration and Development Costs

Geological and geophysical expenses of all kinds may be claimed as an expense and deducted from income.

Well drilling costs, including cost of test wells, deepening wells, and bringing wells into production, or for that matter, the drilling of a well subsequently abandoned, may all be claimed as an expense and deducted from income. This would include cost of roads, surface leases, and casing, but would not include tubing or surface equipment.

Annual rental payments may be deducted as an expense, but not the initial bonus payment for a lease.

* The 1953 Federal Budget has outlined further changes specifically directed towards the easement of taxation of the oil industry, but the alterations have not yet been finalized.

"Dry" hole or "wet" hole contributions may be claimed as an expense.

Deep test wells.—If a group of wells aggregating 25,000 ft of hole or a single deep test is drilled, the operator may claim not only the whole cost of the well as a deduction from the revenue, but also 30 per cent of the cost of the well from the taxes he would otherwise be expected to pay. This can only be done if permission has been obtained from the Lieutenant-Governor-in-General prior to start of drilling operations.

This claim must be made in the year of expenditure, and the wells for which a claim is made must be spudded in 1952 or prior years. It refers only to unproductive wells.

The above expenses can only be deducted if spent in Canada.

An oil corporation, association, partnership, or syndicate can apply these deductions to income made in any branch of its activities, provided the company is connected with the production, refining, or marketing of petroleum products. An individual is not so entitled, neither is a company whose main occupation is not the petroleum business.

Exploration and drilling losses may be carried forward indefinitely until there is income against which they may be written off.

All these regulations apply until 1954, when, theoretically, drilling done thereafter will not be allowed as an expense. All are convinced, however, that these provisions will be extended after 1954 by enactment.

Losses in a Year

The Income Tax Act provides that business losses in a year may be written off against income from the preceding five years or in the succeeding one year.

Depletion

Generally speaking, depletion is allowed, up to 33⅓ per cent of the operator's profits, to the operator on his overall net income from production of oil and gas.

Justice Brandeis of the Supreme Court defined depletion allowance in these words :

> "The depletion charge permitted as a deduction from the gross income in determining the taxable income of mines for any year represents the reduction in the mineral content of the reserves from which the product is taken. The reserves are recognized as wasting assets. The depletion effected by operation is likened to the using up of raw material in making the product of a manufacturing establishment. As the cost of the raw material must be deducted from the gross income before the net income can be determined, so the estimated cost of part of the reserve used up is allowed." [12]

This is a complex subject, and in a short résumé of this kind cannot be covered adequately. For further information the reader is referred to N. D. McDermid.[12]

Partnerships, Syndicate Agreements, Joint Ventures

Joint Exploration and Development.—Each party, being a corporation engaged upon the production, refining, or marketing of petroleum products,

may deduct from its income the expenses it has incurred in the joint venture, irrespective of what percentage that may represent of the total expenditure of the joint venture.

In the case where, as frequently happens, one partner drills a test well to acquire interest in acreage, then only the corporation syndicate, etc., that actually makes the expenditure can deduct the expenditure.

Generally speaking, partnerships, syndicates, etc., of companies not normally engaged upon the oil business cannot deduct drilling and development expenses from the profits of their substantive business. If, however, they contribute income-bearing assets to the financial structure of the joint venture, the expenses apparently are deductible from such income.

Economics of Development

Exploration

In the " plains," on account of the widespread coverage of glacial till, little surface mapping is possible. Such work as has been done has been confined to survey of outcrops along river banks. Generally, this involves plane tabling, as the dips are slight and structures can be detected only by accurate levelling. The cost of this type of survey depends entirely upon the terrain over which the geologist is passing. In the more remote areas it is obviously more expensive than in areas nearer to the main towns and highways.

In the foot-hills the outcrops are much more frequent, and normal geological surveying has been carried out by the Federal and Provincial Governments. Records of these surveys are available from the Department of Mines and Mineral Resources, Ottawa, at small cost to the purchaser.

Aerial photographic work has been done over most of the Province of Alberta, and the examination of these photographs offers a wide field for research. The cost of such a compilation and examination would be of the order of 50 cents per square mile.

By far the greater part of the money spent on exploration has been utilized on geophysical surveys. Of these seismic work has absorbed the most. Contracts may be arranged either on a shot-hole basis, a daily basis, or a monthly basis. The usual prices quoted are $900 per day, $100 to $150 per shot hole, and the figure per month varies usually with the terrain in which the work is done and the duration of the contract; average monthly cost in the prairie areas would be $17,000 to $29,000 in the bush areas.[13]

In the flatly dipping beds encountered, lithological variations—not always due to reefing—cause confusion. Since such large areas are under investigation, most geophysical work is of the reconnaissance type, and it will be a long time before more detailed operations are general. Detailed work by major companies has had a considerable measure of success, due, it is believed, to their experience. The small operator with a 10,000- or 20,000-acre reservation has difficulty in getting his prospect shot, he lacks ability to make a detailed interpretation due to lack of velocity control, and in any event the area covered is only a small one and has no background. The conclusion is drawn that little value is obtained from such seismic work, but rather a long-term programme within the same general

district should be arranged. This larger job makes possible the retention of a reliable seismic party. Such work can be done only if a large area is available, or if many small reservation holders pool their interests. Failing these, it would appear advantageous to concentrate efforts in areas where the precision of seismic work is less critical. One such area is the belt of the Madison scarp, where wedging of Lower Cretaceous sands produces stratigraphic traps, and where farmouts on small reservations are readily available.

Next in importance at the present time is probably core-hole drilling. Prices here range from $1.40 to $1.60 per foot for holes down to 1000 ft. Gravity surveys are conducted at a rate of approximately $5000 per month. Airborne magnetometer surveys have been made, but the prices of these and the contracts in connexion therewith have been kept confidential. All the figures quoted above include the cost of the horizontal and vertical control of the observed points and the cost of any bulldozing, road-making, etc.

Drilling Operations

In Western Canada, as a result of the numerous wildcats that have been and are still being drilled, a differentiation is made between the cost of drilling and the cost of completion. Fig 5 shows the cost of drilling wells to various depths, assuming that an average amount of coring and testing is conducted and that no special difficulties are encountered. These figures also include the cost of acquiring surface rights and the building of a certain amount of road to each location. Under normal circumstances in surveyed territory it is seldom that a company is involved in the building of more than $\frac{1}{4}$ to $\frac{1}{2}$ mile of track from the nearest road allowance to the well. These figures do not include the high cost of transporting the rig great distances from one location to the next.

Production

Costs vary with depths and conditions of production. Most of the wells in the Redwater field, for example, are now on the pump, and a high proportion of the wells in the Leduc field will have to be pumped in the near future. Although there are no sand problems, wax gives trouble, and in certain circumstances corrosion of the pump itself has been a problem. For purposes of making an economic assessment the figure of 50 cents per barrel is generally used for production costs.

Pipeline Charges

The general scheme of oil availability, distribution, and demand is illustrated in Fig 6. The Interprovincial pipeline is already in use, and a pipeline from Edmonton to Vancouver is now under construction.

For companies which do not possess their own pipeline facilities, the disposal of the oil from the batteries and tank farms on the leases can be done in three ways :—

(i) The Imperial Oil pipeline gathering system, which operates in Leduc and Redwater and carries the oil to the main tank farms.

(ii) The transportation of the oil by road tank-car to rail-head and thence to the refinery.

(iii) In areas where the fields are suitably located, oil can be pumped direct into the rail tank-cars and so to the refinery.

The charge for taking the oil into the pipeline gathering system is usually 6 cents per barrel; the charges for road haulage vary with the distance of the oil from the railhead; the charges for rail transport vary with the distance the oil is from its ultimate destination, namely, the refinery.

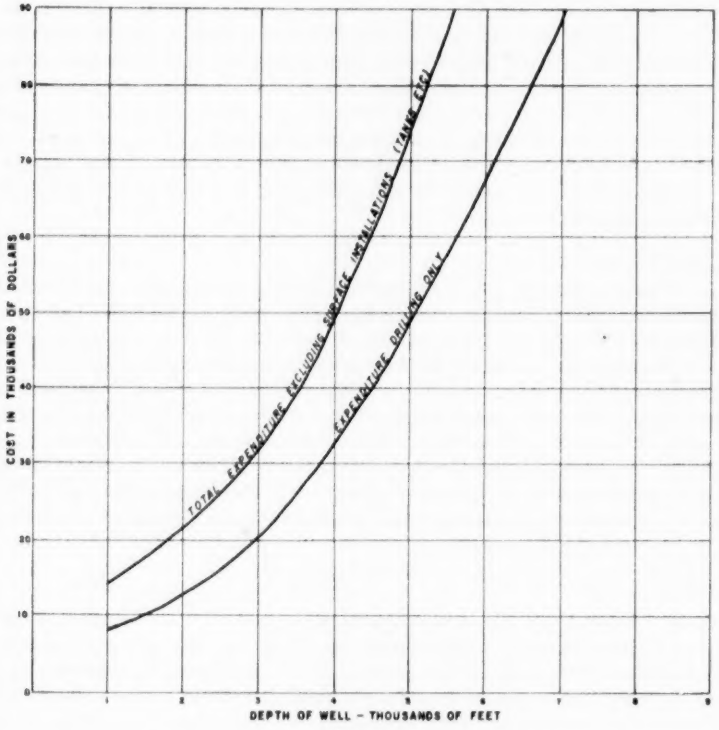

COST IN THOUSANDS OF DOLLARS
DEPTH OF WELL - THOUSANDS OF FEET
TOTAL EXPENDITURE EXCLUDING SURFACE INSTALLATIONS (TANK FARM)
EXPENDITURE DRILLING ONLY

FIG 5

DRILLING AND COMPLETION COST OF WELLS OF VARIOUS DEPTHS IN WESTERN CANADA

All pipelines are buried below the frost level, so there is no cessation of oil flow throughout the year. Road transport occasionally suffers from the spring thaws and snow drifting in winter. Transportation of oil by rail is seldom interrupted.

The destination of the oil may be classified in three ways. First, there is the local disposal of the oil to refineries in Alberta. This amounts to between 70,000 and 80,000 b.d. Then there is the disposal through the Interprovincial pipeline to the refineries in the mid-prairie areas. These absorb approximately 90,000 to 100,000 b.d. Finally, there is the disposal of the oil through the whole length of the pipeline down to Sarnia. In 1952 the take-off at Sarnia was approximately 25,000 b.d.

The Interprovincial pipeline intends to expand its intake from 122,000 to 155,000 b.d. by April 1953. The Trans-Mountain pipeline is expected to be in operation by August 1953 with a throughput of 120,000 b.d., of which 80,000 brl will be shipped to the U.S. and the balance will be absorbed by markets in British Columbia. The ultimate capacity of this line is expected to be 200,000 b.d.

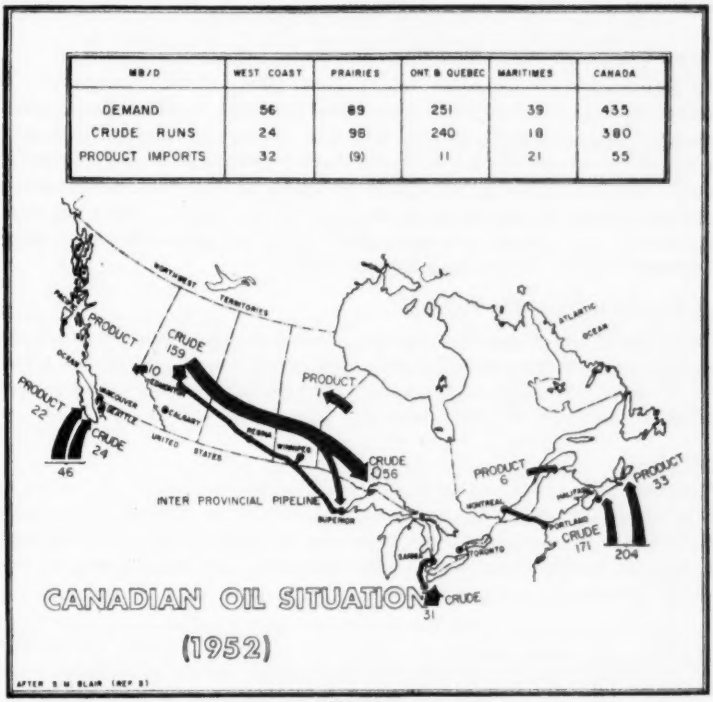


FIG 6

DISTRIBUTION OF CRUDE OIL AND PRODUCTS IN WESTERN CANADA

Return of Capital

The question which faces all companies entering Western Canadian oil development is the rate of return on the capital invested. At the present time this is slow, as the allowables are usually about one-half of the total daily productive capacity of the well, and average 40 to 50 b.d. It is generally thought that the increase in the offtake by way of the Interprovincial pipeline and the Trans-Mountain pipeline will be offset by the increased number of wells to be drilled. It is not anticipated that there will be a substantial increase in the allowable from the individual wells. In considering the available Canadian markets for crude oil, it is of interest to note that the Canadian demand in 1942 averaged 222,000 b.d. and in 1950 averaged 345,000 b.d. In 1951 it averaged 410,000 b.d. Estimates of production in Western Canada anticipate an average daily production in the summer of 1953 of 300,000 b.d.

Canada stands almost without parallel among the nations of the world for its sustained high volume of capital expenditures in relation to national income. It is almost impossible not to visualize an ever-increasing industrialization, not only in Canada as a whole, but particularly in the west. A corresponding increase in future consumption of oil products can be expected.

Types of Deal

The Acquisition of Crown Reservations

The acquisition of leases or reservations direct from Government for annual rentals was the original form of deal by which most of the companies entered the Western Canadian oil picture. Nearly all under this heading have now been absorbed by a large number of companies now participating. However, as time goes on, acreage is returned to Government and put up for a second time at various auctions and sales. There is then an opportunity for the new-comer to acquire these by some form of bonus payment. (See remarks under Leases and Reservations.)

Lease Purchase from Freeholders

Apart from the Canadian Pacific Railways and the Hudson's Bay Company lands, there are still quite a number of leases held by the farmer. Some of these have held out over the years for higher prices, and it is still possible to purchase directly from the farmer himself.

Farmouts

Operators who entered the Western Canadian development earlier and now find that they have too much land to be able to finance all the necessary exploration are often willing to release an interest in some holdings in exchange for development work. This may be done in a variety of ways, of which two are the most common :—

(i) The company desiring to make entry applies for a geophysical option commonly known as " shooting option." Under the terms of such a deal the new company undertakes to do geophysical work within a given period on the original lessee's lease or reservation. On the completion of the geophysical work within the specified period, he is entitled to exercise an option either to withdraw completely on the evidence of the geophysical picture or to drill a test well which will entitle him to an agreed percentage interest in the lease or reservation.

(ii) Possibly the more common of the two types of deal under this heading is to undertake to drill a well within a specified period, which is usually determined by the obligations of the lessee to Government, and in return for this drilling to acquire an interest in lease or reservation. A very large number of variations in this type of deal are at present customary in Western Canada. For example, in the one case the farmee undertakes to drill the well at his entire cost and expense but to recover all of the drilling costs out of production if it is obtained. Under other circumstances the farmee may guarantee to drill the well and complete it at his entire cost and expense and only recover such costs out of his interest in the production which may be obtained. The costs of subsequent wells are shared in the

ratio of the interests held by the parties. For new-comers, it is still quite possible for the farmee to be the operator of the land, as many of the reservations are held by companies who have no facilities for operating their leases.

Purchase of Crude Oil in the Ground

This can be done in two ways, either by purchasing oil from wells which have already been drilled or by purchasing oil in leases which are considered proven, for instance the " Field Parcels " in Crown Sales.

Drilling for an Interest in a Property

This has been a policy adopted by several drilling contractors. The contractor either quotes a " turn-key " job (*i.e.*, a fixed price for the drilling of the well) which is less than the normal price, or he quotes a footage and daily rate which is less than normal. In each case the amount of the reduction in price governs the interest taken.

Participation with Other Companies

Frequently one company will obtain a farmout or a lease with a drilling commitment or a reservation with a geophysical obligation. That company will then solicit contributions and participation from amongst those companies with whom it is accustomed to deal.

Purchase of Royalties

A number of companies have purchased up to one-half of the royalty usually exacted by the freeholder. This has been done more in Saskatchewan than in Alberta. In such cases the purchaser stands to collect royalty in the event that oil is found, or if the lease should default or expire the purchaser's permission would be necessary before a further lease is signed. The purchaser then has the opportunity of leasing the land himself.

Purchase of Royalties in Wells

Syndicates are formed for the purpose of financing an individual well. The organizer will put in sufficient to cover, say, 25 per cent of the cost of the well and then as results grow more promising or even after the well has been brought in he will divide his interest into 100 points and sell each point to give him a profit or to recoup his expenditure and leave him a substantial carried interest.

Mergers of Companies

Although there are large numbers of small companies, a tendency to pool resources has been noticeable, since the rapid growth of many companies has created an acute shortage of competent technical management.

Conclusions

It will have been noted for the information in the earlier sections that conditions in Western Canada differ drastically from those in most countries in which British companies have operated in the past. Table II shows a comparison made between operating conditions in Western Canada and Venezuela.

TABLE II

Comparison of Operating Conditions

Plains of Western Canada (with emphasis on Alberta)	Venezuela
POINTS CONTRA	
Geological Factors	
(i) Fields were hard to find : relative absence of seepage fields.	Earlier fields very easily found. Seepage fields were present.
(ii) Reconnaissance investigation is of less value in appraising land.	Reconnaissance methods are of more value.
(iii) Oil accumulations are mainly in stratigraphic traps of minor dimensions.	Most oil accumulations are in structural and fault traps, except for the enormous stratigraphic accumulations in the Maracaibo area.
(iv) Oil finding, even by detailed seismic work, is difficult.	Detection of structural and fault traps is more positive.
(v) Average field is of modest size. If large fields are excluded (10 per cent by number and in excess of 10,000 acres each) average field size of remaining 90 per cent is less than 1000 acres (analysis by H. H. Suter). Many of the small fields discovered may prove to be marginal.	Corresponding value for Venezuelan fields is more than 1000 acres.
(vi) Multiple horizon fields are less frequent than single zone fields.	Multiple horizon fields are more common.
(vii) Average development well as a rather modest ultimate, estimated at 100,000 to 150,000 brl (analysis by H. H. Suter).	Average wells have a much larger ultimate.
(viii) Average daily production per well is low (about 50 b.d. at end of 1951).	Average daily production per well is higher (220 b.d. in 1951).
(ix) Electric log interpretations is difficult in thin sands and limestones, and recourse must be made to cores and D.S.T.	Electric log interpretation easier in many instances.
Geographic and Climatic Conditions	
(i) Transport of oil by pipeline to remote markets is more expensive than tanker transport and less flexible.	Transport of oil is easy by tanker. Transport from the inland fields is more difficult.
(ii) Winter operations less efficient as a rule, but in some muskeg areas winter operations are actually easier.	Rainy season operations less efficient.
(iii) Activity is dispersed over too large an area, due to intense competition. This has an unfavourable aspect at the present, since it reduces concentration of effort.	Only 16,000,000 acres out of a prospective 62,000,000 acres are under concession.
National and Economic Factors	
(i) Competition is clamorous and promotional investment evident.	Less competition and little promotional activity.
(ii) Lease prices have become high. System of cash bonuses with slow cash return takes form of advance taxation on intangible assets.	Relatively lower prices. Government revenue is very high, but based largely on actual profits.

TABLE II—*continued.*

Plains of Western Canada (with emphasis on Alberta)	Venezuela
POINTS PRO	
Geological Factors	
(i) Exploration costs are low.	Exploration costs are high.
(ii) Area available for exploration is large, which is favourable in the long range.	Area available smaller than in Canada.
(iii) Natural gas is abundant, and its wide-scale exploitation is likely in the near future. (Three gas discoveries to one of oil.)	Natural gas is not in general commercial demand, but still it is applied to secondary recovery.
(iv) Rate of new field discovery is still likely to improve, even with present known methods.	This tendency considered less certain.
(v) Rate of decline of production for individual well is likely to be slow, due to conservation.	Rate of decline expected to be faster.
(vi) Small marginal discoveries, which are favourably situated, have a chance to be evaluated further by additional drilling due to lower development costs.	High operating costs leave less chance for further evaluation of marginal discoveries.
Geographic and Climatic Factors	
(i) Despite large distances involved, access is surprisingly easy.	Apart from the coastal fields, communications are poor and necessitate costly construction work by companies.
National and Economic Factors	
(i) Local capital is freely available for any sound investment.	This aspect has had less application.
(ii) A supply of skilled labour and technicians is available.	Technical personnel are less readily available.
(iii) Development costs are relatively low.	These costs are high.
(iv) Utilities are available.	Generally everything must start from scratch.
(v) Ready availability of supplies enables supply houses to satisfy day to day requirement of operators.	Companies need more elaborate warehouse and storage facilities.
(vi) Local and national need for oil and gas is increasing.	The increase is less marked.
(vii) Producers do not have to bear large capital outlay for oil transportation.	Companies operating inland fields must provide means of transporting oil.
(viii) Petrochemical and other industrial development will provide a demand for gas.	Development of petrochemical industry not yet evident.
(ix) Small companies can readily enter operations due to availability of technical consultants and contractors.	Conditions are prohibitive for the entry of small companies.

The contrast between conditions in Western Canada and Venezuela is quite remarkable. The advantages and disadvantages compensate to the extent that operations in both countries are thriving. Admittedly the fruits of Western Canadian oil search have yet to mature, due to the slow rate of return, but the present high pitch of activity is taken to indicate

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that the large companies regard the future with optimism. The important difference relative to the present discussion is that entry is still possible into the Western Canadian oil industry.

By way of conclusion a few of the topics mentioned in the comparison will be amplified.

" *Lease Prices Have Become High* "

It has become evident that the provincial leasing policy has had a profound influence upon lease prices, leasing, investment, and development. This is most evident in Alberta, where the results of the Government policy have had time to mature.

Let it be assumed that an exploration well drilled on a Government Reservation is a success. Government immediately takes back land in the neighbourhood of the well. The value of this land may now be up to a hundred thousand times its original value.

This acreage is put up for auction by Government in small parcels—generally one or two quarter-sections at a time. The original discoverer is in the best position to bid, and probably wishes to unitize his holdings on the structure; for this he is prepared to consider his investment on the parcels as distributed over the rest of the structure. Competitors must therefore bid somewhat in excess of the calculated expected value of the reserves of the property if they are to outbid the discoverer.

The high prices thus publicly established by Crown Sales become the basis of all surrounding freehold lease transactions. Promoters turn the leases over at a profit within a wide radius of the discovery, regardless of structure, lithology, or trend. The whole area becomes " hot."

This upward flurry of prices spreads outward until it encounters the influence of the next nearest discovery. In this way a recognizable pattern of lease prices is built up, and patently stems from the cash bonus aspect of Crown Sales.

" *Small Companies Can Enter Operations, but with less Technical Efficiency* "

This statement is made in the belief that Western Canadian operations follow trends similar to those in the U.S., where the twenty-two largest companies get about 50 per cent of the oil, but drill only 25 per cent of the wells, and only 20 per cent of wells drilled by the large companies are non-productive, compared with 42 per cent of the small companies wells.

This success is attributed to two main factors :—

(i) Larger companies can afford better lease coverage, with well distributed blocks of adequate size, while the smaller companies are apt to find their blocks so small that they are inadequate to explore and —even in the event of success—they are too small to yield the return that is deserved for the effort.

(ii) Seismic work is credited with the discovery of some of the recent reef discoveries, such as Wizard Lake, Bonnie Glen, Pigeon Lake, and New Norway, and it has already been indicated that successful seismic work requires continuous, large scale operations backed up with company experience. Thus the larger companies are heavily favoured.

" Area Available for Exploration is Large," BUT *" Competition is Clamorous "*

Both these opposing statements apply, and in effect exploration is going on over a tremendous area, but equally it is very thinly spread out. These statements are reflected in the fact that the Alberta Government has not yet fully enforced the drilling obligations that are outstanding. While 240 drilling rigs are currently active, only 116 are engaged in wildcat drilling, which corresponds to one rig per 2500 square miles. Similarly, 183 geophysical parties represents one crew per 1300 square miles, and in view of far higher local concentration in the plains, south of Edmonton, the far larger residual area is even less adequately covered. Thus it is seen that the task of prospecting and drilling to test the oil resources of Western Canada is a vast task which will require very many years.

It has been seen that " free " land with nominal reservation fees is not readily available and that some form of bonus in the form of cash or of work is necessary. This bonus situation is unlikely to change; the pattern is too well established, but—with expenditure commitments mounting and disappointingly low returns from restricted production—better quality lands can be expected to be available for farmout or participation.

" Many of the Small Fields Discovered May Prove to be Marginal "

This statement reflects the fact that discovery wells of marginal aspect are likely to lead to marginal or uncommercial fields; this is a hazard involved in any oil operation. Lists of " oilfields," such as in Table I, include new field discoveries that are " in suspense " until they are proved commercial. The evaluation of some such marginal wells is usually known only to the operators. The economic limit of a marginal well in Canada is certainly lower than in most countries outside the North American continent.

Foot-hills Area

Many of the comparisons made in the tabulation do not apply to the foot-hills. Exploration and drilling costs are high, and geological surprises in the form of repetitions—of the wrong beds—are common. Nevertheless, this area affords opportunity for the more painstaking type of evaluation; structural conditions are more tangible, a geophysical high is less likely to be due to glacial cover or to velocity variations. In the earlier phase of drilling insufficient or no seismic control was available and rigs were not equipped to go to the necessary depths, but now that the exploration can be carried out efficiently, increased activity is expected in the foot-hills.

Acknowledgments

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Discussion

Mr Scott : The great questions which are being debated are : "Has the competition which has caused high lease-prices reached a peak?" and "Will these prices be maintained, or will they fall?" In Alberta itself there is confidence that prices will be maintained or increased as long as the pressure of new money from America continues, and there is not a world-wide recession. At the financial centres in the East and in New York there is divided opinion. It is no longer so easy to attract money into oil-finding ventures, and the poor interest returns on most oil stocks have been noted. On the other hand, the oil refiner in Canada continues to want more Canadian crude, and bona fide producing companies with associated refinery interests are willing to pay highly for well established production. With the slow rate of return on capital brought about by present low production allowables, it is not easy for new entrants to buy proven oil and use the proceeds to expand their operations.

One would feel more confident that the oil industry in Western Canada justifies the large amounts of capital being invested if the prospect were better from the technical angle.

As an oil proposition, the Alberta basin measures below average in com-

parison with the world's major oil basins on a unit area basis. Stratigraphic traps dominate, and these call for much more exploration drilling than do tectonic traps. The average reservoir is thin, if we exclude the D-3 reefs, which are hard to find.

In short, though there is a large area offering possibilities, the costs of exploration will be high, and the average oil pool when found will not be a bonanza.

If gas pipelines are built, and off-take at commercial rates is ensured, conditions may change radically. It may be shown that a normal gas well has a quicker pay-off than a 40 to 50-b.d. oil producer. Thus when imported capital ceases, it may be replaced by revenue from oil and gas combined.

In summary, one can say that the situation is still complex. A second Redwater or Leduc has not yet been found, but satellite reefs such as the Golden Spike–Bonnie Glen trend may offset their declines. New D-3 reef discoveries of the same type are being made between Stettler and Nevis, to the south of the original D-3 hot spot near Edmonton.

The paper does not provide an appraisal of the economics of entering Canadian operations at the present time, but I hope that this aspect will be dealt with in a subsequent paper.

O. F. Thompson: Let us try to put Canadian developments in the perspective of the world background. Canada is currently producing oil at the rate of about 9 million tons a year or about 1½ per cent of world production. To judge from the paper, this rate of production may be rather more than 20 million tons, or about 2½ per cent of world production by 1956. It would seem that considerations of cost may severely restrict Canadian production competing to any important extent in the international oil market.

The paper implies that the potential resources of the country are likely to be very large indeed. Will Canada eventually graduate from a parochial producer to the status of a supplier on an international scale? It would be interesting to know to what extent the authorities are planning to achieve this aim. It will not be achieved by setting heavy work obligations, or by imposing lease and royalty charges which might make production non-commercial. In this connexion, reference is made to depletion allowances on p. 411. In the U.S.A. a depletion allowance on gross profits is allowed, which may be as high as 50 per cent of the net profits, and it seems strange that Canada, or perhaps just Alberta, should impose more onerous conditions.

On p. 413 of the paper production costs are given as 50 cents a barrel. Does this figure include the cost of finding the oil?

On p. 418 an interesting comparison is made with Venezuela, but it is rather like comparing an acorn with an oak tree. Moreover, the authors are in error in saying that the higher Government revenue in Venezuela is based largely on profits. Except for two or three, all companies in Venezuela operate at a loss.

For every oil discovery in Canada there are three gas discoveries, and Canada may become one of the world's greatest gas suppliers. Are operators going to be encouraged to move this gas to the nearest outlets at profitable prices?

E. S. PINFOLD : Could any change in the regulations be suggested which would make the economic situation more favourable to the producers and to the man looking for oil ?

J. B. KAY : In the taking-up of contiguous leases, are the obligations allowed to be spread over such leases, as they are, for example, in the Model Colonial (Oil Mining) Regulations ? These allow the drilling obligation to be spread over two or more contiguous licences, if there is a geological trend which can be shown or supposed to exist covering such licences.

MR PINFOLD : In the Redwater field, something like 900 producing wells have been drilled at 40-acre spacing, as required by the regulations. Would it not have been to the greater advantage of the Province, and of the oil operators, if fewer wells at wider spacing had been drilled at Redwater, and the same drilling resources used in prospecting work in other parts of Alberta ?

T. L. CARR : It was mentioned in the paper that the rate of American investment in the development and production of oil in Alberta and Saskatchewan had declined. To what extent has this been offset by British investment ?

H. C. LACK : What is the present position and future prospects of the Athabaska tar sands ?

C. R. MORGAN : What percentage of the 50 cents per barrel production cost could be attributed to production work in cold areas ? I am thinking particularly of wax troubles in oil wells and hydrate troubles in gas wells.

MR MCMULLEN : In answer to Mr Thompson's question, Canada has already passed the parochial stage. The Trans-Mountain pipeline should be completed by August 1953, and transportation will commence in October at the rate of 135,000 b.d., 75,000 b.d. going to the U.S.A. Twelve miles across the border in the U.S.A. a refinery is being constructed which will absorb 35,000 b.d. of Alberta crude. The Interprovincial pipeline is being extended through the American, instead of around the Canadian, side of the pre-Cambrian Shield. At Superior there is increasing demand for Canadian crude, more and more of which will be tapped-off in the U.S.A. It is said that the Trans-Mountain pipeline has a capacity of 200,000 b.d., but with the addition of two pumping stations to those already planned, the capacity will be 300,000 b.d. A 625-mile extension to the Interprovincial pipeline will export 300,000 b.d. to the East, so that there will be a 2500-mile pipeline with outlets along the way. It may be possible to ship crude once agreement is reached on the building of the St. Lawrence seaway.

The Minister of Mines and Minerals has said that shortly after the meeting of the Petroleum and Natural Gas Conservation Board at Calgary in April 1953, some indication would be given about the early export from Alberta of natural gas. The route which has been surveyed stretches roughly 2400 miles from Southern Alberta into the industrial areas of Toronto and Montreal, and an expenditure of $275 million dollars is

involved. We may see this line completed by 1956, but export may not be authorized in the immediate future.

MR SCOTT: The 50 cents production cost does not include finding or drilling costs, but only those for straight lifting and transport to pipeline. It is sufficient, provided there is not a lot of repair work.

Regarding Mr Pinfold's question, it is difficult to suggest what can be done to improve the pay-back on the amount of revenue put in by the producer.

Prices are dangerously high; I have been told that it requires a capital of $2000 to find each barrel per day of discovered oil in Alberta. This means that a capital sum of $2000 pays $730 annually; this is 36 per cent per annum, assuming that a profit of $2 per barrel can be realized over the first few years. This seems an excellent return if it is agreed that this barrel per day can be maintained for ten years. But it takes about five years to find the oil, and pay-off is spread over ten years. In any case, $2000 for one barrel per day has been about the average rate since the inception of the oil industry in Canada, and I doubt whether one could guarantee to find 3000 b.d. for $6 million now.

Regarding Mr Kay's question, I think that the owner of a lease has definite obligations to drill wells within ninety days on that lease, if the area is productive. One can drill continuously, and then call a halt. I do not think that one can, in Alberta, apply for any relief of payments on reservations on account of expenditures incurred on other leases.

In reply to Mr Carr, I would say that the drying-up of public capital has been slight, and there is no sign that this has happened with total capital. I believe that total capital input is increasing, so I think that the authors were referring to the slight drying-up of public capital in 1952, when there was a definite fall in the price of shares. But the big companies are still investing capital, and to judge by the prices at the Government auction sales, there has been no fall-off at all. Capital from America is invested on a large scale, but the U.K.'s contribution is very small. I refer to the Dominion Bureau of Statistics' recent publication on this point. Canadian and U.S. companies have invested a total of $1.2 billion in Canadian oil to date. The amount spent on exploration and development is roughly $400 million; and refineries, merchandising, and transportation account for the rest.

MR MCMULLEN: With regard to this drying-up of American capital, it now costs the U.S. $1.02 and $1.03 to buy a Canadian dollar. There was as much U.S. investment in Canada in 1952 as in 1951 or 1950. Eighty per cent of the Canadian oil industry is now American financed, 15 per cent is financed by Canadian capital, 5 per cent by French, Swiss, Belgian, and Continental capital, and I regret to say only about 1 per cent by British capital.

MR SCOTT: Regarding the Athabaska tar sands, I think the authors avoided commenting because the subject has already been covered in Mr Blair's reports and in a paper to the Society of Arts in London. Economic extraction of oil from the sands is a very complex problem for the physicists and for the chemists to solve.

MR MCMULLEN : Six major companies have each taken out concessions on blocks of 50,000 acres on which they are doing exploratory drilling to get an assessment of the depth of sand and the overburden, and so on. There are also several syndicates who are doing a great deal of work, and the Swedish Shale Company is testing an *in situ* process to reduce the cost of separation.

MR SCOTT : In answer to Mr Morgan's question, effects of low temperatures seem to be surprisingly small. I have not seen gas wells of the Alberta basin producing—they are mostly shut in—but the Foothills gas wells seem to produce satisfactorily in temperatures down to 20 degrees below, and the oil is not waxy. In the drilling period the difficulties are not great. The rigs are closed in during winter, and coal is used to maintain steam heating all around the rig. Operations are interrupted only during blizzards and thaws.

THE CHAIRMAN : This paper can be looked at in two ways : first, it gives those of us whose work runs in somewhat technical grooves a chance to broaden our ideas of the industry, and secondly, the paper contains much information about the Canadian scene.

I ask you to join with me in thanking Mr McMullen and Mr Scott for the way in which the paper has been presented, and ask them to convey our sentiments to the original authors.

(The vote of thanks was heartily accorded.)

A. BEEBY-THOMPSON (written contribution) : I would appreciate the authors' views on the prospects of a remunerative sale of gas and oil by producers whose allowables are low and liable to diminish with every new discovery. Those having interests in refineries and petro-chemical plants are in a privileged position, but there is a lack of available markets compared with the oil and gas potentialities of the Prairie Provinces.

Cheap electricity and the extended employment of L.P.G. in outlying settlements are likely to be important competitors to oil and gas. Long-distance transport of gas is not cheap, and compares unfavourably with oil transmission by pipeline, due to the great difference in heat values transmissible in pipes of equal size. Much of Canadian gas appears to be contaminated with corrosive impurities that need abstraction before admission to pipelines, and this is likely to be costly unless satisfactory uses for extracted constituents are found and maintained at an economic price.

An interesting point in West Canadian oil and gas developments is that, as in the U.S.A., the reserves of gas and oil are about equal in thermal value. This will doubtless have a bearing on future Government measures of control.

MR LEE and DR YOUNG (written reply) : In reply to Mr Thompson's question concerning outlets for gas discoveries, there have been two quite distinct problems relating to the export of gas : first, export from Alberta to other Provinces, about which there is now little contention *in principle*; secondly, export cross the border, about which there is still much dissension. In the first case, residual opposition arises from economic problems related to the market price of gas in the Eastern Provinces and the possibility that

some form of Government subsidy might be involved. In the second case, both Provincial and Federal Governments of Canada have approved *export* from the Peace River area only. Permission has not been granted for any other areas. The question of right to *import* gas by the U.S. from Canada is now before the U.S. Federal Power Commission. Until this approval has been obtained, no definite steps will be taken to implement the decisions of the Canadian Provincial and Federal Governments to permit *export*.

With regard to Mr Kay's question about contiguous leases, two possibilities are relevant—contiguous reservations and contiguous leases. Regarding contiguous reservations held under one control in remote areas, if a well is drilled or geophysical work done in one reservation, the Minister can be asked for permission to apply a part of the cost of the work in one toward the maintenance of the other. If a well is drilled and abandoned, a decision must be made with respect to both reservations—whether to drill another well, to go to lease, or to drop either or both, according to the status of each reservation. In November 1952 there were 714 active reservations in Alberta—too many to enforce a well being drilled on each reservation.

Secondly, with regard to contiguous leases—contiguous within the restrictions of the regulations—several factors alleviate drilling obligations. In the Act there is a twelve-month obligation on each lease, and in November 1952 there were 19,682 active leases in Alberta, so there is every need for relaxation of this provision. However, the operator may apply for deferment of the obligation. Furthermore, grouping of leases is allowed: a lessee may group leases within a three-mile radius of the well site he proposes to drill. The grouping ceases upon discovery of petroleum, but, generally speaking, one active rig within the area seems to be sufficient to show serious intent.

If the first well is dry and abandoned, a second well should be started within six months, but this can be suspended at the discretion of the Minister. If the first well finds petroleum, the second well should be spudded within ninety days, but, again, the Minister may grant a deferment, and a fair chance to evaluate the commercial possibilities of the well can be assumed.

The following pamphlets cover the Alberta Statutes and Regulations, and may be obtained from the Department of Mines and Minerals, Edmonton, Alberta:—

Applicable to the disposal of petroleum and natural gas owned by the Province—

The Mines and Minerals Act and Amendments.
Regulations governing the Reservation of Petroleum and Natural Gas Rights and Amendments.
Regulations governing the Licensing of Natural Gas Rights.
Petroleum and Natural Gas Royalty Regulations.

Applicable to all drilling and production of oil and natural gas in the Province—

The Oil and Gas Resources Conservation Act, 1950 and Amendment.
The Drilling and Production Regulations.
The Gas Resources Preservation Act.

We should like to answer Mr Pinfold's question concerning the application of 40-acre spacing to field development. The situation at Redwater arose in an early stage of Conservation Board operations, and, although a case might be made for a wider spacing, most of the leases are quarter sections (four 40-acres well sites) with irregular reef pay thicknesses, and equity would have been hard to maintain on edge leases. The Conservation Board has recently recognized a 10-acre development in the Bonnyville area, an 80-acre spacing in the East Drumheller field, and a 120-acre development in the Homeglen area. These cases may be taken as practical evidence of the Board's favourable consideration of such problems.

Further to Mr Scott's comments on the influence of cold climate on production costs, it should be explained that the figure of 50 cents per barrel is a rough average figure that may be applied during the whole production life of a well. During the period of flowing production and the early stages of pumping, the figure is somewhat less. Production costs, including depreciation of equipment, average about $300 per month per well.

Cold weather does introduce extra costs due to the following factors :—

(1) Wax trouble is sometimes encountered in the upper thousand feet of tubing.

(2) Special treaters are needed to heat the oil, to assist in the separation of water.

(3) Flow lines are buried to avoid the low temperature encountered above ground.

Regarding Mr Scott's statement that D-3 reefs are hard to find, some qualification is necessary. These reefs are not technically hard to find, but it is difficult to acquire a stake in them due to high competitive bidding.

In reply to Mr Beeby-Thompson's written contribution, the fact that suitable gas markets are distant remains a significant disadvantage, and will necessitate careful planning for the expensive projects involved. Much of the gas so far discovered, especially that found in the Cretaceous, does not need extensive treatment. On the other hand, gas found in deeper reservoirs, notably that at Pincher Creek, Okotoks, and Jumping Pound, contains appreciable amounts of sulphur, in addition to condensate products. Although the separation of the possible by-products will call for expensive plant, it is anticipated that very appreciable profit will be realized in the process.

In conclusion, we wish to thank Mr Scott and Mr McMullen for their presentation of the paper and for their able answers tendered in the discussion.

THE INSTITUTE OF PETROLEUM

SYMPOSIUM ON EXAMINATION OF USED LUBRICATING OILS

An Ordinary General Meeting of the Institute was held at 26 Portland Place, London, W.1, on 24 March 1953, Mr A. T. Wilford in the Chair.

The Chairman said : The symposium on the examination of used lubricating oils consists of four papers by members of the staff of the Shell Petroleum Co. The papers deal with a particular aspect of the subject, namely, I.C. engine crankcase oils.

Twenty years ago, even the more enlightened users were willing to rely upon the results of the examination of used oil samples when deciding between different grades of oil. It gradually became appreciated that such decisions should be based not so much on the condition of the oil as on the condition of the engines. In the laboratory, this led to the development of engine tests as a means for evaluating lubricating oils; under service conditions, it led to large-scale, long period tests in which the life of the engines between successive overhauls was the most important factor. The examination of used oils did not, however, go out of fashion, for it yielded valuable information which could not be obtained in any other way, and at the same time assisted in deciding upon the optimum period for oil changes. The purpose which it serves in the research and development laboratories of a large oil supplier will be apparent from the papers, which are to be presented in summary by Dr J. B. Matthews.

The following papers were then presented :—

THE DETERIORATION IN USE OF I.C. ENGINE CRANKCASE OILS

By J. B. MATTHEWS *

SUMMARY

Analytical data are presented for a large number of used I.C. engine crankcase oils, taken from engines run under normal operating conditions both on the road and in the laboratory, and also from engines run under abnormal laboratory-controlled conditions. The analytical data consist of the true concentration of oil-insolubles (determined by direct filtration through bacteriological filter pads), the fraction of the oil-insolubles soluble in chloroform, the sulphated ash values of the unused, used, and filtered used oils, and the amount of sludge which is precipitated from the filtered used oil by dilution with petroleum spirit. These analytical data lead to the conclusion that the oil-insoluble phase in general consists of the combustion chamber smoke particles, and perhaps to a minor extent of wear and dust particles, and such particles have sorbed oil oxidation products from the liquid phase. The chloroform-soluble fraction of the oil-insolubles gives a measure of the relative contribution of oil oxidation to the insoluble phase. Only with lightly refined oils under high temperature and good combustion conditions does oil oxidation directly produce an oil-insoluble phase, although under exceptionally high-temperature conditions a naphthenic M.V.I. oil has also given oxidation sludge. This abnormal type of oil-insoluble matter can be readily distinguished from the more normal type under a high-power microscope. No real distinction can be drawn between used oils from diesel and petrol engines, but in both cases the determining factor controlling both the amount and the composition of the oil-insoluble phase appears to be the efficiency of the combustion process.

INTRODUCTION

THEORIES about the causes of the deterioration in use of I.C. engine crankcase oils have fluctuated over the years between the view that the contaminants appearing in the oil, excluding dust, wear, and corrosion products, originate as the products of the combustion process, and the opposing view that all contaminants, apart from those listed above, are due to oxidation of the lubricating oil itself. Thus, Barton and Thorneycroft [1] and Pye [2] were mainly concerned over the question of whether the insoluble " carbon " found in used oils was derived from the combustion of the fuel or of the lubricating oil leaking into the combustion chamber. On the other hand, Burke, Hughes, Scovill, and Bartleson [3] state that " the deterioration of lubricating oil in internal combustion engines is due largely to oxidation reaction," and Davis, Lincoln, Byrkit, and Jones [4] say that sludge and engine dirt is caused by the precipitation from solution of oxidation products of the lubricating oil. The feelings of many people on the subject were perhaps summed up neatly by Pomeroy [5] when he stated, in speaking of sludges and deposits, that " the possible constituents of any deposit are beyond description. . . ." However, a recent summary of the present state of knowledge in this field has been given by Georgi,[6] who inclines to the view that all engine

* Thornton Research Centre, Shell Petroleum Co. Ltd.

deposits are formed from the contamination which is washed into the oil from the combustion chamber, and that oxidation of the oil plays a negligible part in oil deterioration phenomena.

During the years immediately after the war a systematic study of crankcase oil deterioration was made at Thornton Research Centre, and this paper provides the experimental evidence from which certain conclusions concerning the mechanism of oil deterioration have been drawn. The main conclusions, which have already been given,[7] are that the oil-insolubles found in used crankcase oils consist mainly of the solid particles which occur in the exhaust smoke, and that these particles after entering the oil adsorb or absorb oxidation products of the oil, and probably other surface active materials which may be present in the oil. The colloidal behaviour of the oil-insolubles, which is an important factor in engine cleanliness, is largely determined by the surface activity of the sorbed substances. Thus, oxidation of the oil is a significant factor in the deterioration of crankcase lubricating oils and its related phenomena, and this aspect of the subject is discussed in a following paper.[8] The size distribution and the colloidal behaviour of the oil-insoluble particles in the used oils, and the kinetics of the oil deterioration process, which provide support for the theory of oil deterioration advanced in this paper, are also described in later papers.[9, 10]

The Composition of the Used Oils

The standard methods and terminology generally used in the analysis of used engine crankcase oils have been borrowed from the technology of bitumen. With the advent of additive oils, however, these methods have been found unsuitable, and alternative methods have been developed. For example, the standard method for the determination of the sludge content involves dilution of the used oil with petroleum spirit prior to filtration. This dilution step, which causes flocculation of the oil-insolubles, is necessary in order that separation of the insolubles can be effected with the ordinary type of filter. With additive oils, flocculation does not always occur on dilution, and only partial separation of the insolubles is achieved. Furthermore, it has been claimed that dilution causes the precipitation of oil-soluble material and therefore the sludge values obtained by a dilution method do not necessarily represent the true state of the used oil. For these reasons the method developed at Thornton, for measuring the true concentration of oil-insolubles in the used oil samples, employed direct filtration at a temperature of about 90° C through a bacteriological filter, namely a cellulose–asbestos filter pad sold under the trade name of " Sterimat." Specially designed filter holders were constructed from aluminium alloy, and suitable experimental precautions were taken, so that the concentration of oil-insolubles in any used oil could be measured accurately to the second place of decimals expressed as a percentage weight of the oil. The filter holder containing the filter and the separated oil-insolubles could be placed in a solvent extraction apparatus, by means of which the fraction of the oil-insolubles which was soluble in boiling chloroform could be measured.

Other properties of the used oils which were measured were the inorganic ash contents and the precipitable sludge, which is defined as the amount

TABLE I

Properties of Used Oils from Gasoline Engines (Leaded Fuel except where Otherwise Stated)

Oil No.	Engine •	Operating conditions	Duration of operation, hr	Type of oil †	Oil-insolubles, %w	Fraction of oil-insols soluble in chloroform, %w	Sulphated ash values, %w				"Carbon," %w	Precipitable sludge, %w
							Before use	After use	After filtration	Extraneous ash		
1	A	Simulating normal passenger car driving	180	High V.I. (A)	1·97	13	0·45	0·94	0·09	0·49	0·87	Nil
2	A	" " "	180	" "	1·93	8	Nil ‡	0·54	0·03	0·54	1·26	Nil
3	A	" " "	180	" "	0·60	8	0·21	0·34	0·03	0·13	0·24	Nil
4	A	" " "	180	High V.I.	0·65	6	Nil	0·43	0·03	0·43	0·20	Nil
5	A	" " "	180	High V.I. (A)	2·42	15	0·38	1·10	0·08	0·72	1·04	Nil
6	A	" " "	180	" "	1·33	9	0·25	0·82	0·09	0·57	0·48	Nil
7	A	" " "	180	" "	0·95	4	0·14	0·50	0·09	0·36	0·50	Nil
8	A	" " "	180	" "	1·50	15	0·16	0·81	0·11	0·65	0·58	Nil
9	A	" " "	180	" "	1·03	7	0·19	0·70	0·08	0·51	0·34	Nil
10	A	" " "	180	" "	1·12	11	0·19	0·63	0·04	0·44	0·41	Nil
11	A	" " "	180	" "	2·38	10	0·22	0·08	Nil	—	2·06	Nil
12	A	" " "	180	" "	2·57	12	0·25	0·89	0·07	0·64	1·43	Nil
13	A	" " "	180	" "	1·52	10	0·20	0·80	0·02	0·60	0·55	Nil
14	A	" " "	180	" "	1·92	10	0·25	1·04	0·06	0·79	0·75	Nil
15	A	Simulating winter town driving	15	" "	0·31	39	0·26	0·23	0·10	—	0·06	—
16	A	" " "	15	" "	0·30	37	0·16	0·27	0·17	0·11	0·09	—
17	A	Normal road operation	1000 miles	High V.I.	0·61	20	Nil	0·25	Nil	0·25	0·24	Nil
18	A	" " "	1000 miles	" "	0·48	21	Nil	0·15	Nil	0·15	0·23	Nil
19	A	" " "	1000 miles	" "	0·37	27	Nil	0·15	Nil	0·15	0·12	Nil
20	A	" " "	1000 miles	" "	0·40	25	Nil	0·16	Nil	0·16	0·14	Nil
21	A	" " "	1000 miles	" "	0·40	25	Nil	0·24	Nil	0·24	0·06	Nil
22	A	" " "	2514 miles	High V.I. (A)	0·68	15	0·40	0·78	0·28	0·38	0·08	Nil
23	A	" " "	1077 miles	" "	0·21	43	0·19	0·15	0·07	—	0·04	—
24	B (C)	High temperature	96	" "	1·31	3	0·39	1·01	0·25	0·62	0·51	Nil
25	B (C)	" "	96	" "	0·99	6	0·39	0·63	0·27	0·24	0·57	Nil
26	B (C)	" "	96	" "	1·89	18	0·39	0·45	0·02	0·06	1·12	Nil
27	B (C)	" "	96	" "	0·11	36	0·39	0·59	0·49	0·20	—	Nil
28	B (C)	" "	96	" "	0·99	16	0·39	0·52	0·31	0·13	0·62	Nil
29	B	" "	96	Low V.I.	0·17	35	Nil	0·09	Nil	0·09	0·02	0·26
30	B	" "	96	" "	0·17	6	Nil	0·10	Nil	0·10	0·06	<0·05
31	C	" "	90	High V.I. (A)	0·41	15	0·15	0·33	0·09	0·18	0·11	Nil
32	C	" "	70	" "	0·60	13	0·39	0·64	0·19	0·25	0·07	Nil
33	C	" "	150	" "	0·63	5	0·26	0·47	0·13	0·21	0·26	Nil
34	C	" "	124	" "	0·46	6	0·16	0·61	0·14	0·45	—	Nil
35	D	Normal road operation	—	High V.I.	0·03	33	Nil	0·05	Nil	0·05	—	Nil
36	D	" " "	—	" "	0·27	44	Nil	0·12	Nil	0·12	0·03	Nil
37	E	" " "	—	" "	0·99	20	Nil	0·20	Nil	0·20	0·59	Nil
38	F	" " "	4000 miles	" "	0·39	31	Nil	0·11	Nil	0·11	0·16	Nil
39	F	" " "	4464 miles	High V.I. (A)	0·14	7	0·19	0·15	0·06	—	0·04	—
40	F	" " "	1972 miles	" "	0·35	26	0·19	0·34	0·04	0·15	—	—
41	G	" " "	9476 miles	" "	0·29	21	0·19	0·22	0·08	0·03	0·09	—
42	G	" " "	4439 miles	" "	0·39	31	0·19	0·11	<0·02	—	0·17	—
43	G	" " "	933 miles	High V.I.	0·38	21	Nil	0·12	Nil	0·12	0·18	—
44	G	" " "	2028 miles	" "	0·42	29	Nil	0·13	Nil	0·13	0·17	—
45	H	" " "	275 miles	High V.I. (A)	0·61	15	0·19	0·13	Nil	—	0·39	—
46	I	" " "	963 miles	High V.I.	0·25	24	Nil	0·13	Nil	0·13	0·06	—

• (C) indicates unleaded fuel. † (A) indicates that the oil contained a metallic additive. ‡ The oil contained a non-metallic additive.

TABLE II

Properties of Used Oils from Diesel Engines (Unleaded Fuel Except where Otherwise Stated)

Oil No.	Engine	Operating conditions	Duration of operation, hr	Type of oil †	Oil-insolubles, %w	Fraction of oil-insols soluble in chloroform, %w	Sulphated ash values, %w				"Carbon," %w	Precipitable sludge, %w
							Before use	After use	After filtration	Extraneous ash		
47	J	Normal	25	High V.I. (A)	0·97	6	0·09	0·12	—	0·03	—	Nil
48	J	"	25	" "	0·40	5	0·53	0·60	0·49	0·07	0·27	—
49	J	"	25	" "	0·46	—	0·10	0·11	0·07	0·01	—	Nil
50	J	"	25	" "	0·29	—	0·30	0·30	0·27	Nil	—	—
51	J	"	25	" "	0·15	—	0·28	0·28	0·26	Nil	—	—
52	J	"	25	" "	0·17	—	0·29	0·33	0·29	0·04	—	—
53	J	"	25	" "	0·39	15	0·27	0·30	—	0·03	—	Nil
54	J	"	25	" "	0·31	20	0·25	0·25	—	Nil	—	Nil
55	J	"	25	" "	0·32	12	0·26	0·28	—	0·02	—	Nil
56	J	"	25	" "	0·23	4	0·26	0·30	—	0·04	—	—
57	J	"	25	" "	0·66	—	0·11	0·11	—	Nil	—	Nil
58	J	Power-house operation	2000	" "	0·65	18	0·40	0·37	0·14	—	0·30	Nil
59	J	" "	2000	" "	0·59	25	0·40	0·38	0·14	—	0·20	Nil
60	J	Normal "	25	High V.I.	0·16	7	Nil	0·02	—	0·02	—	—
61	J	"	25	Med. V.I.	0·25	4	Nil	0·02	—	0·02	—	—
62	J	"	25	" "	0·20	10	Nil	Nil	—	Nil	—	—
63	J	"	25	Med. V.I. (A)	0·58	—	0·20	0·20	—	Nil	—	Nil
64	J	"	25	" "	0·42	7	0·21	0·24	—	0·03	—	—
65	K	"	545	High V.I.	1·01	10	Nil	0·03	Nil	0·03	0·88	Nil
66	K	"	380	" "	0·65	—	Nil	0·04	Nil	0·04	—	Nil
67	K	"	300	" "	0·98	10	Nil	0·07	Nil	0·07	0·81	Nil
68	K	"	640	" "	0·64	11	Nil	0·07	Nil	0·07	0·50	Nil
69	L*	"	144	High V.I. (A)	4·05	3	0·69	0·80	0·47	0·11	3·60	Nil
70	L	"	144	" "	4·74	6	0·70	0·75	0·54	0·05	4·25	Nil
71	L	"	224	Med. V.I.	5·23	2	Nil	0·11	0·02	0·11	5·04	Nil
72	M	"	480	High V.I. (A)	0·11	54	0·38	0·45	0·38	0·07	—	Nil
73	M	"	480	" "	0·22	23	0·19	0·25	0·10	0·06	0·02	Nil
74	N	"	419	" "	2·41	8	0·24	0·28	0·21	0·04	2·15	Nil
75	N	"	500	" "	2·57	4	0·23	0·32	0·22	0·09	2·37	Nil
76	O	"	—	Med. V.I. (A)	1·32	9	—	0·16	0·03	—	1·07	Nil
77	O	"	—	" "	1·52	13	—	0·24	0·04	—	1·12	Nil
78	P	"	—	High V.I. (A)	0·42	40	0·24	0·09	0·03	—	0·19	Nil
79	Q	"	—	Med. V.I.	0·13	8	Nil	Nil	Nil	Nil	0·12	—
80	R	"	>2 yrs	" "	1·15	—	Nil	0·18	Nil	0·18	—	Slight precipitate

* Leaded fuel used.

† (A) indicates that the oil contained a metallic additive.

of sludge that precipitates from the filtered used oil on dilution with ten volumes of 60° to 80° C petroleum spirit, expressed as a weight percentage of the original oil. The inorganic ash determinations were carried out, in the presence of excess sulphuric acid, on the used oil before and after Sterimat filtration to remove the oil-insolubles, with the precaution that the temperature was not allowed to rise above 600° C in order to avoid loss of metals like zinc and lead.

The results obtained from the examination of used oils obtained from both automotive gasoline and diesel engines, operated under a variety of conditions, are given in Tables I and II. Most of these oil samples came from engines which had been run under fixed test conditions, but these had generally been chosen to simulate road conditions with emphasis on different aspects, such as sludging and piston lacquering. The results obtained with used oils taken from vehicles operated under normal road conditions, when compared with the used oils from test engines, show that the oil deterioration process is essentially the same in both cases, although differences do occur which are presumably due to differences in operating conditions. Comparison of the data with those for used aircraft piston engine oils has also shown that the deterioration process in aircraft engines is essentially the same as that which occurs in automotive engines, one marked difference being the much greater amount of lead compounds found in the former.

The total concentration of oil-insolubles is a variable factor, and again there is little, if any, difference between gasoline and diesel engines. Among the latter a wide variation exists, Engine L apparently producing about twenty times as much oil-insoluble matter as Engine M with similar oils. The higher concentrations of oil-insolubles from Engine L is almost certainly due to the known greater tendency of this engine to produce " soot " in the combustion chamber. Although the total amount of insolubles is higher for Engine L than for Engine M, the chloroform-soluble fraction of the oil-insolubles is higher for the latter. Again, the chloroform-soluble fraction of the combustion chamber " soot," collected from the exhaust gases, is very low compared with that of the oil-insolubles taken from the lubricating oil of the same engine (see Table III). However, if the exhaust " soot " is stirred

TABLE III

Comparison of Exhaust Soot and Oil-insolubles from Tests in Diesel Engine J

Oil No.	Fraction of exhaust soot soluble in chloroform, %w	Fraction of oil-insolubles soluble in chloroform, %w
56	1·0	4
60	1·1	7
61	0·9	4
62	0·8	10

with oxidized lubricating oil it adsorbs oxidation products from solution in the oil, which can then be subsequently extracted from the oil-insolubles by chloroform extraction in about 80 per cent yield, after the oil-insolubles have

been filtered from the oil, washed with petroleum spirit, and dried. These results indicate that the chloroform-soluble fraction of the oil-insolubles is a measure of the oil oxidation products contained in them.

If the sum of the chloroform-soluble fraction of the oil-insolubles and the insoluble inorganic material (given to a first approximation by the difference in sulphated ash values between used oil and the filtered used oil) is subtracted from the oil-insolubles, the value obtained can be regarded as being the amount of organic oil-insoluble matter which has entered the oil from the combustion chamber. These values are given in Tables I and II in the columns headed " Carbon." The " carbon " values are plotted against the

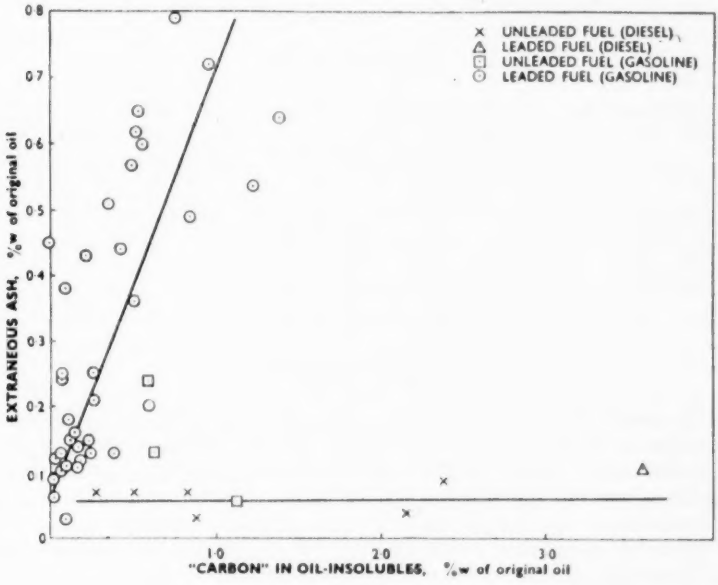


FIG 1

RELATIONSHIP BETWEEN EXTRANFOUS SULPHATED ASH AND " CARBON "

values of " extraneous ash," which are given by the differences between the sulphated ash values of the oil before and after use, in Fig 1. It will be observed that the extraneous ash values for engines run on unleaded fuel are fairly constant, and apparently are independent of the " carbon " values. For engines run on leaded fuel, however, there appears to be a linear relationship between the " extraneous ash " and the " carbon," which indicates that both are derived from the same source. Since lead compounds are the major constituents of the " extraneous ash " when leaded fuel is used, this result confirms the view that the " carbon " is essentially the combustion chamber " soot."

The variation in the concentration of oil-insolubles, and hence of the " carbon " values, from one engine to another would therefore appear to be

dependent on the efficiency of the combustion process. A less efficient combustion process produces a greater concentration of " carbon " particles in the smoke, and therefore a higher concentration of oil-insolubles. Confirmation of this conclusion is provided by the results in Table IV, which were obtained from Engine B run at different fuel mixture strengths.

It will be seen from Table IV that the concentrations of total oil-insolubles and of " carbon " are very sensitive to the strength of the fuel mixture. The negative " carbon " values obtained with normal fuel mixture strength

TABLE IV

96-hr Test Data on a High V.I. Oil Containing Additive to 0·4%w Sulphated Ash Value in Engine B

Oil No.	Jacket temp, °C	Sump temp, °C	Fuel mixture strength	Sulphated ash values, %w			Oil-insolubles			
				Unfiltered (x)	Filtered (y)	($x - y$)	Total, %w of total oil	$CHCl_3$-soluble fraction of oil-insolubles, %	"Carbon," %w of total oil	$CHCl_3$-soluble fraction of organic oil-insolubles, %
81	136	60	Rich	0·45	0·02	0·43	1·90	18	1·12	24
82	157	60	,,	0·63	0·26	0·37	0·99	7	0·55	11
83	166	60	,,	0·52	0·32	0·20	0·99	16	0·63	20
84	177	60	Less rich	0·53	0·36	0·27	0·62	27	0·18	49
85	224	60	Normal	0·61	0·50	0·11	0·09	70	−0·08	100
86	230	60	,,	0·60	0·50	0·10	0·11	40	−0·03	100
87	236	130	,,	0·57	0·42	0·15	0·10	50	−0·10	100
88 *	218	60	,,	0·04	Nil	0·04	0·07	43	Nil	100

* This was a high V.I. oil containing no additive.

are undoubtedly due to an accumulation of errors introduced by the assumptions made in their calculation, but nevertheless the results as a whole strongly suggest that in this gasoline engine, when the operating conditions provide maximum combustion efficiency, no " soot " is produced to contaminate the lubricating oil. The oil-insolubles then consist of the inorganic oil-insolubles, which, like the " carbon " particles, will be able to sorb oxidation products from the oil. Several tests carried out in a motored engine B (in which, of course, combustion was eliminated altogether) gave results confirming the above conclusion. The concentration of oil-insolubles in the used oils produced in this way in six tests varied between 0·05 and 0·11 per cent, the concentration of inorganic oil-insolubles varied between 0·01 and 0·03 per cent, and within the limits of experimental error the concentration of " carbon " was uniformly nil

Most of the oils described in Tables I and II were solvent refined high V.I. oils, and it should be noted that the only oils which contained precipitable sludge (Nos. 29, 30, and 80) were either a lightly refined low V.I. oil or a medium V.I. oil. In the former case 96 hr high temperature operation in Engine B gave used oils which after filtration produced measurable amounts of insolubles on dilution with petroleum, whereas in the latter case a very long period of use under unknown service operating conditions was apparently necessary in order to produce a trace of precipitable sludge. That a naphthenic medium V.I. oil can yield precipitable sludge under exceptionally high temperature conditions is shown by the results given in Table V.

On the other hand, the same medium V.I. oil gave no precipitable sludge at all in diesel engines (Oil Nos. 61, 62, 71, and 79 of Table II and data in Table VI).

TABLE V

Used Oil Data from 64-hr Tests in Engine B on a Naphthenic Medium V.I. Oil at a Sump Temperature of 130° C and a Jacket Temperature of 100° C (Normal Fuel Mixture Strength)

Oil No.	Oil-insolubles, %w	$CHCl_3$-soluble fraction of oil-insolubles, %	Precipitable sludge, %w
89	0·87	—	2·82
90	1·28	98	3·14

The existence of large amounts of precipitable sludge in the used oils would be consistent with the theory of Davis, Lincoln, Byrkit, and Jones [4] that the oil-insolubles are formed as an end-product of the oxidation of the oil. According to this theory the initial oxidation products are oil-soluble, but become progressively less soluble until they are eventually precipitated, and the conversion of the precipitated matter to the final end-product is accompanied by a decreasing solubility in organic solvents. If this theory was correct, it would follow that the chloroform-soluble fraction of the oil-insolubles would decrease with increasing period of use, and that at every stage of the deterioration there would be some precipitable sludge. On the other hand, in a high-temperature test in Engine B, under the same conditions and on the oil that had also yielded Oils 29 and 30 in Table I, it was found, as shown in Table VII, that the chloroform-soluble fraction of the oil-insolubles increased with increasing period of use. No simple explanation for this behaviour can be offered. However, it is feasible that in the early stages of the test, before the oxidation of the oil has proceeded very far, the relative contribution of the combustion chamber solids or inorganic oil-insolubles is high, giving a low chloroform-soluble fraction. In the later stages of the test the production of oil-insolubles by oxidation of the oil may swamp the contamination of the oil from the combustion chamber or from inorganic matter, and this fact, coupled with the high rate of oil consumption due to the large samples withdrawn, may be the cause of the increase in the chloroform-soluble fraction.

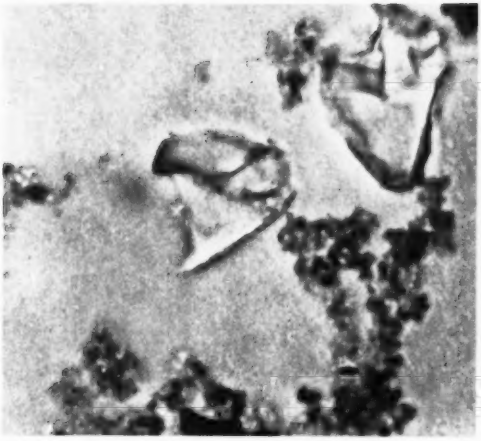
Under a high-power microscope it is easy to distinguish the oil-insolubles produced directly by oxidation of the oil from the normal type of oil-insolubles consisting of " carbon " particles which have adsorbed oil-soluble oxidation products. Fig 2 (*a*) shows laboratory produced oxidation sludge from the low V.I. oil referred to in Table VII in transmitted light at a linear magnification of 1000 times. This sludge, which is 98 per cent soluble in chloroform and consists of large lumps, is partially translucent, the translucent portions appearing golden-brown in colour. The insolubles in Oils 89 and 90 from Table V, as shown in Fig 2 (*b*), were similar in appearance to the oxidation sludge in Fig 2 (*a*), as also were the insolubles in Oil 123 described in Table VII. On the other hand, the oil-insoluble particles in a normal used oil containing no oxidation sludge, such as a used naphthenic

TABLE VI

Used Oil Data from Various Diesel Engine Tests on a Naphthenic Medium V.I. Oil

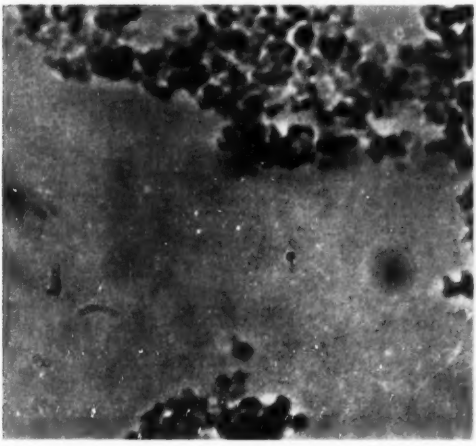
Oil No.	Engine	Operating conditions	Duration of operation, hr	Total oil-insolubles, %w	$CHCl_3$-soluble fraction of oil-insolubles, %w	Sulphated ash of used oil, %w	Sulphated ash of filtered used oil, %w	$CHCl_3$-soluble fraction of organic oil-insolubles, %	Precipitable sludge, %w
91	J	Normal	25	0·25	8	0·02	—	8	Nil
92	J	,,	25	0·27	15	Nil	—	15	Nil
93	J	,,	25	0·23	13	—	—	—	Nil
94	J	,,	25	0·09	33	—	—	—	Nil
95	J	,,	60	1·15	7	0·12	Nil	8	Nil
96	J	,,	60	1·08	18	0·06	Nil	19	Nil
97	J	,,	60	1·59	7	0·13	Nil	8	Nil
98	J	,,	60	1·20	7	0·16	Nil	8	Nil
99	J	,,	60	0·71	10	0·12	0·01	12	Nil
100	J	,,	60	1·00	20	0·11	Nil	23	Nil
101	J	,,	60	0·68	3	0·11	Nil	4	Nil
102	J	,,	60	1·81	6	0·11	Nil	6	Nil
103	L	Varying jacket temperature	40	0·18	40	0·01	Nil	41	Nil
104	L	,, ,,	40	0·11	9	0·20	0·13	25	Nil
105	L	,, ,,	40	0·30	13	0·02	0·01	14	Nil
106	L	,, ,,	40	0·36	30	0·05	0·02	33	Nil
107	K	Normal	500	0·30	40	0·02	Nil	43	Nil
108	K	,,	312	0·39	15	<0·02	Nil	16	Nil
109	K	,,	288	0·30	23	<0·02	Nil	24	Nil
110	K	,,	310	0·52	27	<0·02	Nil	27	Nil
111	S	Varying combustion chamber design	37	0·13	23	—	—	—	Nil
112	S	,, ,, ,,	37	0·24	17	—	—	—	Nil
113	S	,, ,, ,,	37	0·34	12	—	—	—	Nil
114	S	,, ,, ,,	37	0·31	26	—	—	—	Nil
115	S	,, ,, ,,	37	0·58	38	—	—	—	Nil
116	M	Normal	120	0·13	23	—	Nil	—	Nil
117	M	,,	240	0·15	20	—	Nil	—	Nil
118	M	,,	360	0·13	31	—	Nil	—	Nil

(*a*)



Oxidation sludge produced in the laboratory

(*b*)



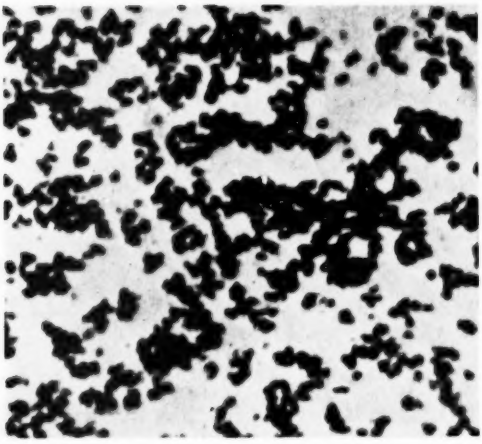
Oil-insolubles produced by Engine B in medium V.I. oil at high operating temperatures

FIG. 2 (*a* and *b*)

PHOTOMICROGRAPHS OF OIL-INSOLUBLES. ORIGINAL MAGNIFICATION 1000 ×

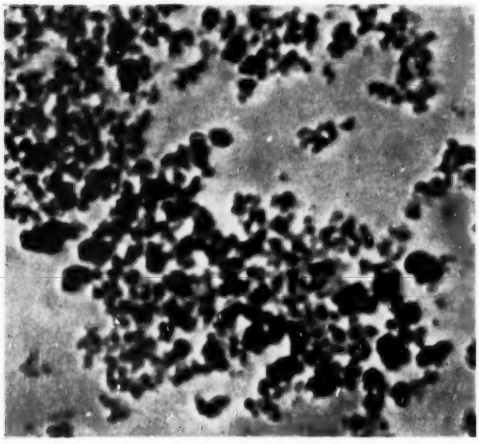
[*To face p.* 135

(*c*)



Oil-insolubles produced by Engine L in medium V.I. oil under normal conditions

(*d*)



Oil-insolubles produced by Engine B in low V.I. oil at high operating temperatures

FIG. 2 (*c* and *d*)

PHOTOMICROGRAPHS OF OIL-INSOLUBLES. ORIGINAL MAGNIFICATION 1000 ×

TABLE VII

High-temperature Engine B Test on a Low V.I. Oil

Oil No.	Period of test, hr	Neutralisation value of used oil, mg KOH/g	Saponification value of used oil, mg KOH/g	Fuel diluent, %w	Water diluent, %w	Viscosity, Red. I/ 140° F, seconds	Oil-insolubles, %w	$CHCl_3$-soluble fraction of oil-insolubles, %w	Precipitable sludge, %w
119	32	—	4·6	—	—	272	0·38	74	—
120	64	—	4·8	—	—	313	0·44	85	—
121	96	—	6·5	—	—	357	0·54	92	—
122	128	—	7·3	—	—	370	0·57	94	—
123	160	2·2	10·0	1	Nil	374	0·65	100	1·9

medium V.I. oil from Engine L (Fig 2 (*c*)), are fairly uniformly sized black particles, which tend to cluster together but do not adhere to each other very strongly.

DISCUSSION

The evidence presented in this paper leads to the conclusion that there are two possible ways in which organic insoluble matter is formed in the crankcase oil during engine operation. It can appear as the direct result of oxidation of the lubricating oil, but this has only been observed with lightly refined oils with a low V.I. under high-temperature operating conditions, and with a naphthenic M.V.I. oil at exceptionally high operating temperatures. Always, however, contamination of the oil by combustion chamber smoke particles occurs, except under the most perfect of combustion conditions. In addition, a small amount of inorganic contamination consisting of wear products or dust normally enters the oil, but usually the amount of inorganic contaminant on a weight fraction basis is smaller than the amount of organic contaminants, and on a particle number basis is smaller still because of the density difference between the inorganic and organic contaminants. In the next paper [9] more detailed information will be given concerning the size distribution of the oil-insoluble particles, together with other data related to particle size which supports the theory of oil deterioration advanced in this paper.

The oil-insoluble contaminants, whether organic or inorganic, adsorb (or perhaps, more correctly " absorb " in view of the relative quantities concerned) oil oxidation products from solution, to give a composite oil-insoluble particle consisting of a smoke, wear, or dust particle plus oil oxidation products. The oil oxidation products and other polar constituents of the oil are probably distributed in equilibrium between the liquid phase and the solid particle phase, as usual with absorbent or adsorbent particles suspended in a solution of surface-active matter. The sorbed oxidation products can be almost completely removed from the separated solid phase by extraction with boiling chloroform, and this method of analysis provides a measure of the relative contributions of external contamination and oil oxidation to the formation of the oil-insoluble phase. When the concentration of external contaminants is high, as in the case of some diesel engines, or in gasoline engines run under rich mixture conditions, the equilibrium concentration of oxidation products in oil solution will be low. In such cases the external contaminants maintain the liquid oil phase in a fairly fresh condition by a

continuous form of "earth treatment" conducted in the engine. The potential amount of sludge increases, however, with increasing concentration of oil-insolubles. On the other hand, as will be shown in a following paper,[8] some of the oxidation products sorbed from the liquid phase by the insoluble contaminants are good dispersing agents and assist considerably in preventing deposition of the oil-insoluble particles as sludge. In this context by sludge is meant the dry form of sludge. Wet sludge, consisting of an emulsion of water in oil stabilized by the oil-insoluble particles, can also form in engines under low operating temperature conditions, but the effect of the oil oxidation products on this type of sludge is not known.

Acknowledgment

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THE SIZE DISTRIBUTION AND COLLOIDAL BEHAVIOUR OF THE INSOLUBLE PARTICLES IN USED I.C. ENGINE CRANKCASE OILS

By H. C. Evans * and J. B. Matthews *

Summary

Particle size distribution measurements have been carried out on typical used crankcase lubricating oils by a micrographical method, a sedimentation method in a normal gravitational field, and a centrifugal sedimentation method. The results are in good agreement and show that the individual carbonaceous particles, which usually constitute the major part of the solid phase in used oils, fall within a very narrow size distribution range, the average diameter being in the region of 1 μ. The observations made in this paper support the conclusion that the carbonaceous oil-insoluble particles originate as smoke particles in the combustion zone.

These particles often exhibit a tendency to flocculate under static conditions, which is influenced by the presence of surface-active substances. The forces being very much weaker, flocculation is less rapid in oil than aggregation of combustion chamber smoke particles is in the gas phase. The minimum amount of dispersant additive required to produce complete de-flocculation appears to be the amount necessary to give a close-packed adsorbed monomolecular layer on the particle surfaces. There appears to be some connexion between the tendency of the particles in the oil to flocculate and crankcase cleanliness of the engine.

Introduction

In the previous paper,[1] used I.C. engine crankcase oils are described as being dispersions of oil-insoluble particles in the partially oxidised lubricating oil. It is obviously of interest to know the size distribution of the insoluble particles and their colloidal behaviour, since both are important in relation to the filtration of the insolubles from the oil and to the formation of sludge. The measurement of the size distribution of the insolubles is not easy, and little information has been published on this subject. Hilfreich, McNicol, and Rosenfeld [2] have published data on the particle size of insoluble matter contained in used I.C. engine crankcase oils, but their measurements were made on the insoluble inorganic matter separated from the oils, and consequently have very little bearing on the particle size distribution of the insoluble organic matter, which constitutes the greater part of the normal contamination found in used crankcase oils from gasoline and diesel engines. Semenido [3] has stated that the greater part of the insoluble carbonaceous material present in used aircraft engine oils consists of particles having diameters between 0·8 and 1·5 μ. The measurements described in this paper support Semenido's statement, and indeed show that the used oils can be considered as being almost monodisperse systems, the particle diameter being in the region of 1 μ.

The insoluble particles will usually flocculate under static conditions, and it has been found that the tendency to flocculate varies considerably with different oils. As expected, some of the additives used in modern crankcase lubricating oils exhibit a strong de-flocculating action on the oil-insoluble

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particles, and a limited correlation has been found between the tendency to flocculate and the crankcase cleanliness of the engine.

Experimental

Particle Size Distribution

Three methods of measuring the particle size distribution of the oil-insoluble particles were used. These were the direct measurement on the photomicrographs of the used oils, the sedimentation method under gravity, and the centrifugal sedimentation method. The micrographical method is the easiest, and the average diameter is quickly obtained, but it is not a convenient method for determining particle size distribution. Suitable conditions under which to make the observations were achieved by using a very thin film of oil, in thickness approximately that of the depth of focus, on a microscope slide. The two sedimentation methods possess the advantage that they give the size distribution without calling for tedious particle counts. The gravity method, however, is slow, measurements on one oil taking several weeks, and the centrifugal method is subject to various errors, the chief of which are due to temperature variations and vibrations.

Both sedimentation methods are subject to errors arising from the effects on the sedimentation rate of the interaction between particles and the wall effect. From centrifugal experiments Martin [4] concluded that no mutual interference between the particles occurs if their concentration is less than 3 per cent by volume. Hawksley [5] has pointed out, however, that Martin's lowest concentration was 0·5 per cent, and whilst it may be argued that there appeared to be no observable interference within the concentration range 3 to 0·5 per cent, experimental data are required for much lower concentrations before a satisfactory conclusion can be drawn, since Burgers [6] on theoretical grounds claims that a concentration as low as 0·002 per cent is required for free settling. Rose [7] found an increase in the apparent particle size calculated from sedimentation data as the concentration of particles increased from 1 to 20 g/litre, and according to Odén [8] Brownian movement may be appreciable when the particle diameter is less than 0·5 μ. Since the concentration of insolubles in the oils examined was of the order of magnitude of 1 per cent and the average particle diameter was about 1 μ, the sources of error mentioned above cannot be excluded.

In fact, when all the possible errors are considered, most of which have been previously discussed in detail,[9] the conclusion is inescapable that no technique is yet available which will give reliable absolute values for particle dimensions in the sub-sieve range. Nevertheless, the values given in this paper can be considered to be reasonably accurate and certainly of the right order of magnitude. This conclusion is supported by the good agreement obtained with the three methods employed, which is presumably due to the remarkable fact that the used oils are apparently to all intents and purposes monodisperse systems.

Micrographical Observations

A Vickers projection microscope was used for the examination of oils in which the insolubles had previously been thoroughly dispersed by mechanical shaking for 2 hr. The magnification employed varied between 780 and

TABLE I

Average Diameters of Oil-insolubles in Used Oils

Oil No.*	3	4	5	6	7	8	9	24	31	32	33	56	66	67	69	71	72	73	74
Average particle diameter in μ	0·9	0·9	1·0	0·9	1·0	0·8	0·8	0·9	1·0	0·9	0·9	0·9	1·1	1·0	0·9	0·8	1·0	1·1	0·9

* For details of the oils see Tables I and II in previous paper.[1]

TABLE II

Average Diameter of Particles Observed as a Function of Period of Use

Oil No.*	Hours of use :	15	16	30	40	50	56	70	80	90	104	110	120	130	144	150	160	170	180	208	224
5	Average particle diameter in μ	0·7	—	0·7	—	0·8	—	0·8	0·8	0·8	—	0·8	—	0·9	—	0·9	—	1·0	1·0	—	—
7	Average particle diameter in μ	—	—	0·9	—	1·0	—	1·0	—	1·0	—	1·0	—	0·9	—	—	1·0	—	1·0	—	—
71	Average particle diameter in μ	—	0·8	—	0·9	—	0·9	0·9	—	0·9	0·8	0·8	0·8	—	0·7	—	0·9	—	—	0·9	0·8

* The Oil Nos. refer to the end-of-test oils, details of which are given in Tables I and II of the previous paper.[1]

1250. In Table I are given the average diameters of the particles in various used oils, obtained by averaging about fifty particles chosen randomly from the field of view recorded photomicrographically.

Numerous oils, with and without additives, have been examined after use in both gasoline and diesel engines under various operating conditions, and Table I shows that the average particle diameter is within the range 0·8 to 1·1 μ. The particles in samples of oil taken at intervals during an engine test sometimes show small variations in average diameter, but these have not in any single engine test amounted to more than 0·3 μ. Table II gives typical results for the variation of the average particle diameter of the particles during the course of an engine test; and Table III gives the diameters of all the particles lying within a small area of the photographic plate for three of the oils.

The only obvious difference under the microscope between periodic samples taken during engine operation is that at the beginning there are few

TABLE III

Diameters in μ of All Particles Within a Given Area

Oil 5 (150 hr operation)
1·0, 1·0, 1·0, 1·0, 1·0, 0·8, 1·0, 1·0, 0·6, 0·8, 1·0, 0·8, 0·8, 0·8, 0·8, 1·0, 1·0, 1·2, 0·8, 0·6, 1·2, 1·0, 0·6, 0·8, 1·2, 1·0, 1·2, 0·8, 1·0, 0·8, 0·8, 1·0, 1·0, 0·6, 1·0, 1·0, 1·0
Oil 56 (after 23 hr)
0·8, 0·6, 0·6, 1·0, 1·0, 0·8, 1·0, 1·2, 1·2, 0·8, 1·0, 0·6, 0·6, 0·8, 0·8, 1·0, 1·2, 1·0, 0·8, 0·8, 1·0, 0·6, 0·8, 1·0, 0·6, 0·6, 1·2, 0·8, 0·8, 1·0, 1·2
Oil 73 (after 73 hr)
1·0, 1·0, 1·0, 0·8, 0·8, 0·8, 1·0, 0·8, 1·0, 1·4, 1·4, 1·0, 0·8, 0·8, 1·0, 1·0, 1·6, 1·4, 0·8, 0·8, 0·8, 1·0, 0·8, 1·0, 0·8, 0·8, 0·8, 0·8, 1·0, 1·0, 1·6, 1·0, 1·0, 1·4, 1·4, 0·8, 0·8, 0·8, 0·8, 0·8, 1·4, 0·8

insoluble particles, but these increase in number, but negligibly in size, as the period of use of the oil increases. Fig 1 illustrates the changing appearance of the oil, viewed statically, as the period of its use increases, and also shows the importance of viewing the oil at a sufficiently high magnification to reveal the individual oil-insoluble particles. The two series of photographs at different magnifications were taken of the same slides without disturbance. It is obvious that at 75× magnification the individual particles cannot be seen, and when particles appear at this magnification these really consist of flocs of individual particles.

The data in Table III can be used to obtain an estimate of the size distribution. From the given values the statistical standard deviation is $\pm 0{\cdot}2$ μ. Assuming that there is a normal distribution and that the standard deviation is the same for all samples, this means that 95 per cent of the particles have diameters within $\pm 0{\cdot}4$ μ of the average values. In fact, the standard deviation works out to be of the same order of magnitude as the possible

error of measurement, which serves to show how narrow the range of size distribution is. Further information on size distribution is obtained from the sedimentation measurements described below.

Sedimentation Measurements in Normal Gravitational Field

In the calculation of particle sizes from sedimentation data, values are required of the densities of the solid and liquid phases, the viscosity of the liquid phase, and the concentration of the insolubles. The density and the viscosity of the liquid phase were obtained by the standard methods on the oils after filtration through Sterimat bacteriological filters, and the concentrations of oil-insolubles were determined by the method indicated previously.[1] The density of the oil-insoluble particles was obtained by calculation from the densities of the oil before and after filtration and the concentration of oil-insolubles.

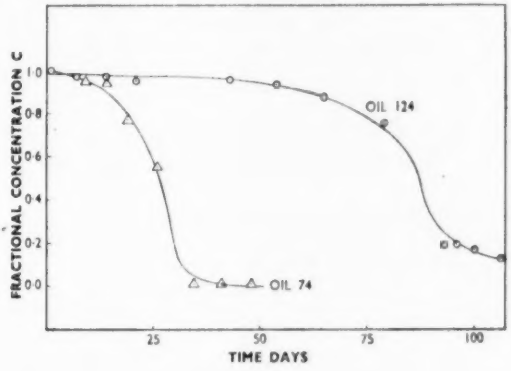


FIG 2

SEDIMENTATION OF INSOLUBLES FROM USED OIL

The used oil, after a preliminary thorough shaking to obtain complete dispersion of the insoluble particles, was left undisturbed in a Winchester bottle at 25° C, and 10-ml samples were carefully withdrawn at intervals by a pipette immersed to a constant depth. The concentration of the insolubles in these samples was measured by the Sterimat filtration method.[1] In this way the variation with time of the concentration of insolubles at a fixed depth of the bulk oil sample was determined, and the results are shown in Fig 2 for the two oils examined in this way. Assuming that Stokes' rule holds, we have :—

$$18\eta h = d^2(\rho_1 - \rho_2)gt \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in which ρ_1 and ρ_2 are the densities of the particle and liquid medium respectively, η is the viscosity of the medium, g is the gravitational constant, and h is the distance fallen by a particle of diameter d in time t. As shown by Odén [8] :—

$$F(d) = -\frac{2t}{d} \cdot \frac{\partial C}{\partial t} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

in which the frequency function $F(d)$ is defined as the weight fraction of particles per unit diameter interval, corresponding to the particle diameter d, and C is the fractional concentration of the insolubles at the depth h, *i.e.*, the ratio of the actual concentration at depth h at time t to the original concentration.

Values of $\partial C/\partial t$ at different values of t can be obtained graphically from the curves in Fig 2, and the corresponding values of d are obtained from equation (1). Substituting these values in equation (2) to obtain $F(d)$ as a function of d, the curves given in Fig 3 were obtained, which represent the particle size distributions of the insolubles on a weight basis as a function of diameter.

Centrifugal Sedimentation Measurements

In this method the weight of material which sediments under centrifugal forces is measured. The theoretical treatment has been fully dealt with by

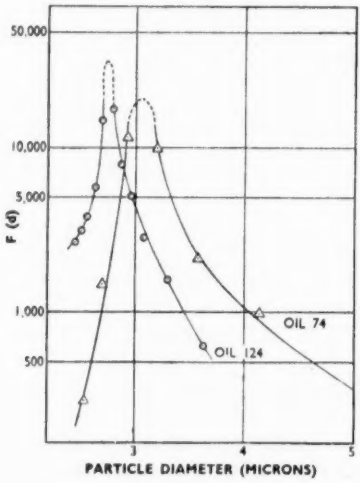


FIG 3

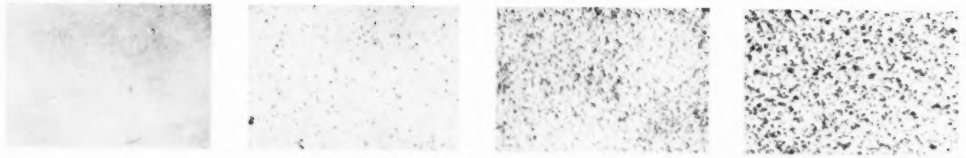
PARTICLE SIZE DISTRIBUTION BY GRAVITATIONAL SEDIMENTATION

Romwalter and Vendl,[10] but more recently Brown [11] has stated that their treatment is incorrect, because at one stage the assumption is made that the particle size is constant. The correct equation for the distribution function is complicated and impossible to solve. Hence, Brown suggests that sedimentation should be measured not as a function of time keeping the length of the liquid column constant, as performed by Romwalter and Vendl, but as a function of length of liquid column keeping the time constant.

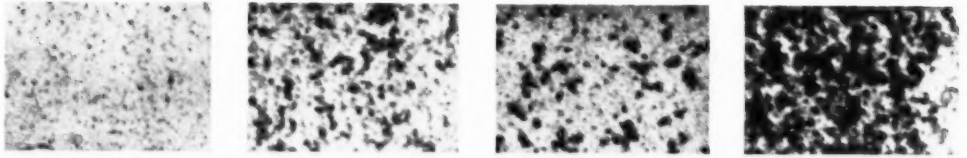
The relevant equation for cylindrical tubes is then :—

$$\int_0^d F(d)\partial d = (r - s)\frac{\partial p}{\partial s} + (1 - p) \quad . \quad . \quad . \quad . \quad (3)$$

in which s and r are the distances of the inner and outer levels of the liquid



Original magnification 75 ×



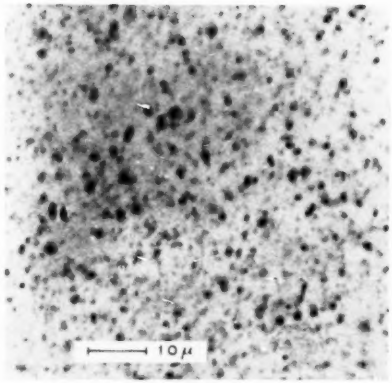
After 16 hours | After 40 hours | After 48 hours | After 56 hours

Original magnification 1000 ×

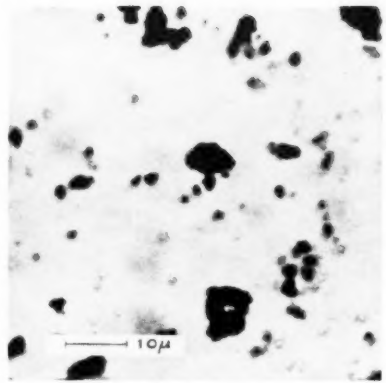
FIG 1

COMPARISON OF PHOTOMICROGRAPHS AT 75 AND 1000 × MAGNIFICATION OF A USED OIL SAMPLED AT VARIOUS PERIODS OF ENGINE OPERATION

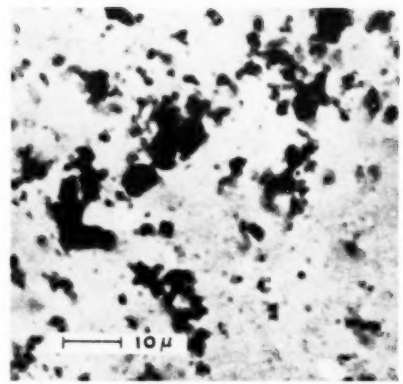
[To face p. 446.



Original particles



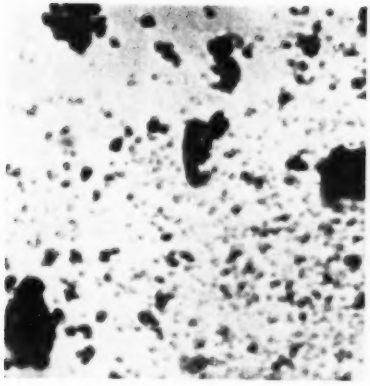
Particles after separation



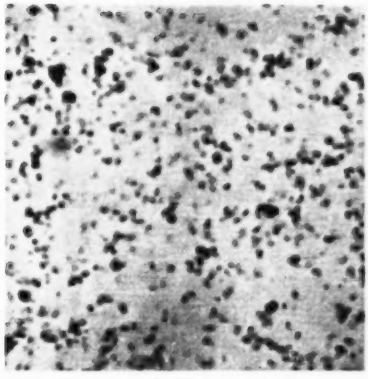
Particles after separation and redispersion

FIG 5

EFFECT OF SEPARATION OF OIL-INSOLUBLES FROM OIL 37 ON THEIR SIZE



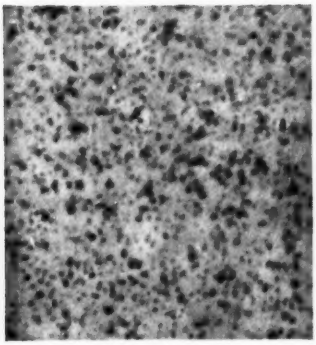
"Carbon" collected from exhaust of a diesel engine



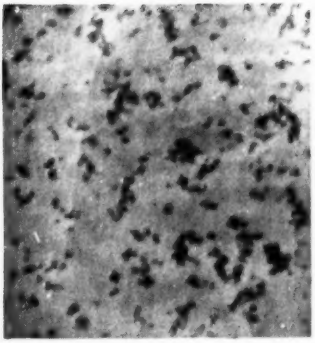
Same "carbon," as above, dispersed in oxidized oil by stirring

FIG 6

EFFECT ON PARTICLE SIZE OF DISPERSION IN OIL OF EXHAUST SOOT. ORIGINAL MAGNIFICATION 1000 ×

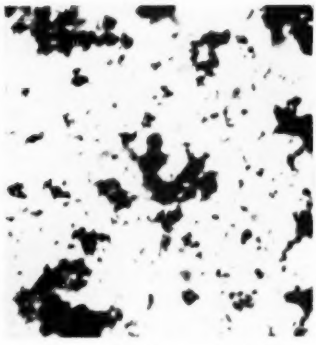


(*a*) After heating and stirring

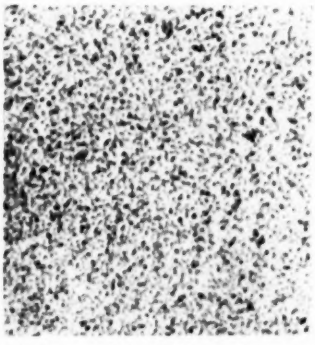


(*b*) As (*a*), with addition of 2·5 per cent anti-oxidant additive

Used Oil ex Engine K



(*c*) After heating and stirring



(*d*) As (*c*), with addition of 0·1 per cent dispersant

Used Oil ex Engine J

FIG 7

EFFECT OF ADDITION OF ADDITIVE TO USED ENGINE OILS. ORIGINAL MAGNIFICATION 1000 ×

column from the centre of rotation, and p is the weight fraction which has sedimented.

Values of d are obtained from the following form of Stokes' Law :—

$$\frac{\partial x}{\partial t} = \frac{\rho_1 - \rho_2}{18\eta} d^2\omega^2 x = kd^2x \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

in which $\partial x/\partial t$ is the sedimenting velocity of the particle, x is the distance of the particle from the centre of rotation, ω is the radial velocity, and $k = \omega^2(\rho_1 - \rho_2)/18\eta$.

By re-arrangement and integration between the limits $x = r$ and $x = s$ equation (4) can be transformed into :—

$$kd^2t = \log \frac{r}{s} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

which gives the required values of d on substitution of the appropriate values of r, s, and t.

Then, by plotting $\int_0^d F(d)\partial d$ against d, and taking tangents to the curve, values of $F(d)$ are obtained. The values obtained for four oils are given as a function of particle diameter in the size distribution curves shown in Fig 4.

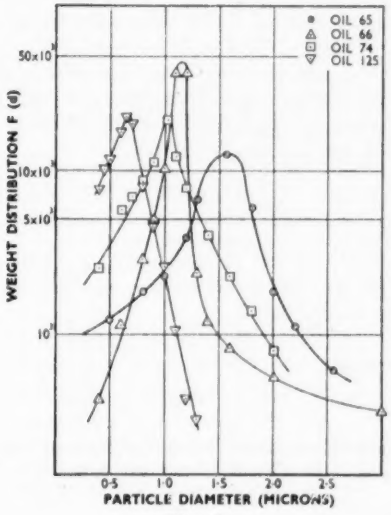


FIG 4

PARTICLE SIZE DISTRIBUTION OF INSOLUBLES BY CENTRIFUGAL SEDIMENTATION

The experimental data were obtained in the following way. The centrifuge tubes, after the addition of different amounts of used oil, were placed in their sheaths and balanced in pairs by floating layers of filtered used oil on the surfaces of the used oil. After centrifuging, the oil was carefully drained off from the sediment, which was then washed free of oil by shaking it with

petroleum spirit and centrifuging to bring down the insolubles. After three washes the sediment was dried at 130° C and weighed.

Comparison of Particle Size Results

In comparing the results obtained by the micrographical and sedimentation methods it is obvious that the *average* particle diameter given by the former is not identical with the *most frequent* diameter given by the latter. The most frequent diameter is given by the apex of the distribution curve, and this only becomes the average diameter if the curve is symmetrical about the apex.

The average particle diameter $\bar{d}$ cannot be determined over the whole range of particle size distribution from the distribution curve, but the average diameter $\bar{d}_1$ of all particles with diameters between zero and the most frequent diameter d_m is given by :—

$$\bar{d}_1 = \frac{1}{F(d_m) - F(O)} \int_{F(O)}^{F(d_m)} d\partial[F(d)] \quad . \quad . \quad . \quad . \quad (6)$$

from which it follows that :—

$$d_m - \bar{d}_1 = \frac{1}{F(d_m)} \int_0^{d_m} F(d)\partial d \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Thus, $(d_m - \bar{d}_1)$ can be obtained directly from the distribution curve, and the results obtained ranged from 0·11 to 0·44 μ for the five oils examined by the sedimentation methods. Obviously the values of $(d_m - \bar{d})$ will be less than those of $(d_m - \bar{d}_1)$, and, since the latter are within the range of experimental error involved in these measurements, it is safe to assume that d_m and $\bar{d}$ can be regarded as interchangeable. With this assumption the average particle diameters are compared in Table IV.

TABLE IV

Average Particle Diameters of Oil-insolubles (μ)

Oil No.*	66	74	124	125
Sedimentation results :—				
Normal gravity	—	3·1	2·8	—
Centrifugal	1·2	1·1	—	0·7
Micrographical measurement :—				
Individual particles	1·1	0·9	1·0	0·7
Flocs	None	4·5	2·5	4·0

* Details of Oils 66 and 74 are given in Table II of the previous paper.[1] Oil 124 was obtained from diesel Engine K after 550 hr normal operation on a medium V.I. oil, and Oil 125 was obtained from diesel engine L after 224 hr normal operation on the same medium V.I. oil.

It is obvious that results obtained by sedimentation under normal gravity, which is carried out statically, gives the size distribution of the flocs of the individual particles. On the other hand, in the centrifugal sedimentation method, possibly because of the vibrations caused by the operation of the centrifuge, flocculation is not allowed to occur, and therefore the size distribution obtained is that of the individual particles.

The curves in Fig 4 indicate that most of the particles in the oils belong

to a fairly narrow particle diameter range, and this is supported by the calculated data given in Table V. By comparison with a typical size distribution of graphite which has been colloidally milled (Table VI) the used oils can be considered to be very close to monodisperse systems.

TABLE V

Spread of Particle Diameters about the Most Frequent Value

Oil No.*	Wt % of particles within the two ranges below of mode diameter	
	$\pm 0{\cdot}15\ \mu$	$\pm 0{\cdot}25\ \mu$
65	54	63
66	71	86
74	44	62
125	51	66

* For details see footnote to Table IV.

TABLE VI

Size Distribution of Graphite Obtained from a Colloid Mill

Diameter range $\times 10^4$, cm	Percentage of particles
400–25	2·8
25–4·8	43·6
4·8–1·0	43·3
1·0–0·1	10·3

As shown by analysis,[1] nearly all the oil-insoluble particles are carbonaceous, except under very efficient combustion conditions. However, inorganic wear and corrosion products and dust particles also occur in used oils, and such material has been separated and examined by Hilfreich, McNicol, and Rosenfeld.[2] In their extreme cases this inorganic material consisted of particles ranging in diameter from less than 1 μ to about 10 μ, and from less than 1 μ to nearly 100 μ. Furthermore, the maxima in their size distribution curves correspond to diameters of 1 to 2 μ. Therefore, the major part of the inorganic matter will be indistinguishable from the carbonaceous particles under the microscope. In addition, using the size distribution of the inorganic particles given by Hilfreich, McNicol, and Rosenfeld, a rough estimate shows that in a typical used oil only one inorganic particle of diameter greater than 2 μ will appear for every 350 carbonaceous particles of diameter 1 μ. For inorganic particles greater than 5 or 10 μ the frequency of occurrence will be very much smaller.

The photomicrographs given by Hilfreich, McNicol, and Rosenfeld, in which numerous large particles appear, are of inorganic particles which have been *separated* from the oils and mounted in collodion, and should not be regarded as representing used oils. Apart from the considerations given above, the process of separating insoluble particles from the used oil alters the size distribution completely. In Fig 5 are shown the oil-insoluble particles in Oil 37 (Table I of previous paper [1]) as they appear in the oil, the

same particles after filtration from the oil, washing with petroleum spirit and drying, and the dried particles after re-dispersion in an unused medium V.I. lubricating oil. It is obvious that very great caution should be exercised in considering the sizes of particles which have been removed from their original environment for purposes of examination.

Flocculation of the Oil-insoluble Particles and its Relation to Engine Cleanliness

As already stated, when disturbing forces are reduced to a minimum, the oil-insoluble particles in the used oils often flocculate. The forces tending to cause this type of flocculation are very weak, and for this reason it is necessary to distinguish this phenomenon from the type of flocculation which occurs between the individual " soot " particles in the combustion chamber smoke, or between the oil-insoluble particles when they are removed from the oil and dried. In the second type of flocculation, which will be referred to as aggregation, the forces binding the particles together are relatively very strong. Thus, when the smoke particles issuing from the combustion chamber in the exhaust gas are collected on an oiled microscope slide they exhibit a wide range of particle sizes, but all the particles appear to be aggregates of individual particles of the same diameter as the individual particles in used lubricating oil. These aggregates, however, require large forces, such as those produced by vigorous rubbing in oil, to de-flocculate them. Fig 6 shows the appearance under the microscope of exhaust " soot " collected in bulk from a diesel engine exhaust and transferred to a dry slide, and a dispersion formed by vigorously stirring the same " soot " in an oxidized lubricating oil. On the other hand, in the case of used oils it is necessary to leave the prepared microscope slide undisturbed for periods up to 1 hr for flocculation to occur, and these flocs are readily dispersed again by the slightest disturbance.

The addition of lubricating oil additives can affect the flocculation of the particles, according to the type of additive used. From an examination of the effects produced by various additives (see Fig 7 for typical results) it was found, in general, that anti-oxidants in some cases had no effect, in other cases promoted flocculation, and sometimes de-flocculated the oil-insolubles. Dispersant additives, the function of which is to improve crankcase cleanliness, invariably showed a strong de-flocculating action. Experiments were carried out in which varying concentrations of a typical dispersant additive were blended into a standard used oil at 60° C, and the resulting blends were then examined micrographically for evidence of flocculation. The blending operation was found to have no effect itself on the degree of flocculation in the used oil, but the additive showed the usual de-flocculating action, and by a suitable choice of additive concentration it was possible to determine the minimum concentration to produce complete de-flocculation. In addition, it was shown, by measuring this critical concentration in a series of dispersions made from the same used oil by dilution with its own filtrate, that the critical concentration was proportional to the concentration of oil-insolubles. Thus, the critical concentrations of the additive for different used oils can be made strictly comparable by expressing them as quantities per unit concentration of oil-insolubles. The results obtained are given in Table VII.

Analysis of Oils 127 and 128 after addition of the critical additive con-

centration showed that, within the limits of measurement, all the additive had been adsorbed by the oil-insoluble particles. Simple calculations, based on the assumption that the oil-insoluble particles are spherical, thus give the particle surface area per adsorbed additive molecule at the critical concentrations as 20 A^2 for the oil from Engine J and 70 A^2 for the oil from Engine L.

TABLE VII

Critical Concentrations of a Dispersant Additive in Various Used Oils

Oil No.*	Concentration of oil-insol, %w	Critical concentration of additive, %w	Critical concentration per unit concentration of oil-insolubles, %w
126	0·75	0·075–0·10	0·10–0·13
126A	0·38	0·04–0·05	0·11–0·13
126B	0·15	0·02–0·025	0·13–0·17
127	0·69	0·10	0·14
128	5·30	0·15 –0·25	0·028–0·047
129	0·94	0·025–0·035	0·028–0·037

* Oil 126 was a medium V.I. oil obtained from diesel Engine J, Oils 126A and 126B were made from Oil 126 by dilution with its own filtrate, and Oils 128 and 129 were medium V.I. oils obtained from diesel Engine L.

When due allowance is made for the probable honeycomb structure of the individual particles, these areas are of the correct order of magnitude to be expected if the adsorbed additive forms a fairly close-packed monomolecular layer.

The above results afford an explanation for the observation illustrated in

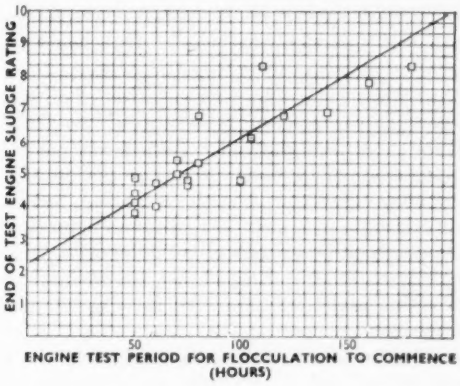


FIG 8

RELATION BETWEEN SLUDGE RATING AND FLOCCULATION RATING

Fig 1. The concentration of oil-insolubles, generally speaking, increases in a regular manner with operating time, whereas the total amount of additive in the oil remains constant, or usually decreases as the result of decomposition, hydrolysis, and so on. Hence, in the early stages of operation the critical concentration will be exceeded by the amount of additive present,

but at some later stage the concentration of effective additive in the oil will be less than the critical concentration, and therefore flocculation becomes apparent.

The flocculation of the oil-insoluble particles is a measure of their tendency to escape from their environment, and is dictated by the surface energy of the particle/oil interface. It is to be expected that the adhesion of the particles to solid walls will run closely parallel to their adhesion to each other,[12] so that crankcase cleanliness should be related to the flocculating tendency of the oil-insoluble particles in the crankcase. In Fig 8 are given some results which are in agreement with this deduction. The average sludge cleanliness ratings in Fig 8 were assessed from the appearance of the rocker cover, the pushrod cover, the sump, and the timing case, at the end of 180-hr tests in Engine A operating under the same conditions which produced Oils 1 to 14 in Table I of the previous paper.[1] These end-of-test values have been plotted against the engine operating time required for the initial appearance of flocculation in static samples of the circulating oil examined under the microscope, and it will be seen that a rough linear relationship appears to hold between the two parameters. Two of the oils were straight mineral oils, and all the others contained dispersant additives. Oils containing additives other than dispersant additives, such as anti-oxidant additives with no dispersant properties, gave results which did not fit in with those shown in Fig 8.

Discussion

The oil-insoluble particles discussed in this paper are those which are normally found in used crankcase lubricating oils, and do not include the oil-insoluble matter produced by direct oxidation of medium or low V.I. oils in engines operating at high temperatures.[1] The size characteristics of the individual particles support the view that these originate in the combustion chamber.[1] If they were formed by precipitation of oil oxidation products from solution, some manifestation of growth would be expected, and also an induction period for their precipitation. In fact, the particles appear in the oil at the commencement of its use, and as the period of use increases the particles do not change significantly in shape or size, but merely increase in number. On the other hand, if they were derived from the colloidal milling between piston ring and cylinder wall of solid deposits perhaps formed there (say, from the oxidation of thin films of oil), there should be a definite distribution over a wide diameter range. In fact, the diameter range of the particles is very narrow.

The work of Whytlaw-Gray and collaborators [13] has shown that the particle size distribution of smokes is dependent on the method of production. Smoke produced by volatilizing solids such as zinc oxide, in such a way that the smoke initially is concentrated, contains particles covering a wide diameter range, the larger particles being formed by collisions of smaller ones. When precautions are taken to dilute the smoke as soon as it is formed, it is monodisperse initially, and only becomes polydisperse slowly on ageing. Thus, conditions in the combustion chamber of an engine are suitable for the production of a monodisperse smoke. Hence, if the oil-insoluble particles originate as smoke particles, as deduced elsewhere, there

is a rational explanation for their monodisperse character. By the time the smoke has reached the end of the exhaust pipe sufficient collisions have probably taken place to give the heterodisperse character of the particles in the exhaust gases. The distance from the combustion zone to the lubricant film on the cylinder walls is much shorter, and it is possible that the amount of aggregation which has occurred in the gas phase prior to the entry of particles into the oil is much less. In any case the rubbing to which the particles in the oil film will be subjected between ring and cylinder wall is probably sufficient to cause deflocculation.

On entering the oil the smoke particles sorb naturally occurring surface-active substances in the oils, additives, and oil oxidation products. The first two groups of substances can exert a deflocculating action, and so also can certain oil oxidation products.[14] These factors, together with the environmental factor, probably account for the much weaker tendency of the particles to flocculate in the oil phase than they exhibit in the gas phase. Sludge deposition in engines cannot be attributed to an increased rate of sedimentation due to flocculation, since the agitation to which an oil is subjected in an engine will prevent flocculation occurring. In any case, sludge deposition often occurs on vertical surfaces and on the underside of engine parts. Undoubtedly, sludge deposition is due to the " escaping " tendency of the oil-insoluble particles, and, as Fig 8 shows, the flocculating tendency is a rough guide to sludging tendency. However, since the rule illustrated in Fig 8 cannot be applied to all oils, it seems that flocculation in the bulk of the oil does not necessarily always run parallel with sludging. Other factors are involved, and it is quite conceivable that, since sludge deposition involves a third phase, *i.e.*, the engine surface, it will be determined by the relative adhesion energies of the particle and the oil for this surface, rather than by the adhesion between the particles themselves.

Acknowledgments

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THE ROLE OF OXIDATION IN THE DETERIORATION IN USE OF I.C. ENGINE CRANKCASE OILS

By J. H. T. Brook,* J. B. Matthews,* and R. P. Taylor*

Summary

The significance of lubricating oil oxidation tests is discussed with particular reference to the catalytic conditions employed. From experimental data it is deduced that two lacquer-forming reactions may occur in engines. The first is a slow reaction, the effects of which can be predicted from oxygen absorption measurements on the oil, provided that the appropriate catalytic conditions are chosen for the test. The second is a much more rapid reaction, which only occurs above a critical temperature dependent on the oil, is controlled by an adsorption mechanism, and is mainly responsible for ring-sticking caused by oil oxidation.

Apart from the deleterious results produced by oil oxidation, some beneficial results can be obtained if a certain class of oxidation product is produced in service in sufficient quantity. In engine tests this oxidation product prevents sludge deposition and improves ring-sticking properties.

Introduction

The effects of the interaction between lubricating oil and fuel on the deterioration in use of the former, and on the general fouling of the engine, have been described in the previous papers,[1, 2] which have dealt with the formation of oil-insolubles in the lubricating oil and the sludge produced from them. Another important aspect of engine fouling is the formation of lacquer on pistons and other engine parts subjected to high temperatures. It is generally accepted that both lubricating oil and fuel can contribute to the formation of this lacquer, the relative contributions being controlled by engine design and operating conditions, as well as by the relative merits of the oil and fuel. From which ever source the lacquer is derived, however, it can be attributed to oxidation. This paper discusses the part played by the oxidation of the lubricating oil on engine fouling.

Correlation of Oxidation Tests with Performance of Lubricating Oils

Oxygen Absorption

A great deal of study has been given to the oxidation stability of oils intended for use in I.C. engines, and a very large number of oxidation tests have been proposed for the simulation of engine performance in simple apparatus. Little information is to be found in the literature giving the correlation of such oxidation tests with engine performance, but it is generally known that some tests show very little correlation with performance.

The problem of obtaining agreement between laboratory oxidation tests and engine performance has been investigated by Larsen, Armfield, and Whitney,[3, 4] who showed that three oils could be placed in any of the six possible orders of merit by varying the catalytic conditions of the oxidation test, thereby demonstrating the importance of giving close attention to the catalyst to be used in the test. Their solution to the problem was to

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use "crankcase catalyst," consisting of the dried oil-insoluble fraction obtained by centrifuging large batches of used oils drained from crankcases, since they had concluded that the oxidation stability of the used engine oil was largely determined by the strong catalytic activity of this oil-insoluble matter. The present authors found, however, that this catalyst, when used in an oxygen-absorption test, gave results which could not be correlated with piston cleanliness performance test results obtained with a small gasoline engine, despite the fact that piston fouling in this engine is known from other evidence to depend mainly on the quality of the lubricating oil. In addition, from a detailed study of the reaction mechanism of the catalysed oxidation of lubricating oils,[5] no support could be found for the view that metal or other surfaces are in themselves catalytically active, but strong evidence was found in favour of the conclusion that the dissolved metallic compounds produced by corrosion reactions were the only important catalysts to be considered. It is obviously a difficult problem to start with solid metal catalysts and to establish the appropriate experimental conditions of the laboratory test so that both the corrosion and the oxidation reactions would simultaneously simulate those that occur in an engine. If reliance is placed on solid catalysts the chances of successfully correlating the results of a laboratory oxidation test with those of engine performance tests are therefore slender, but greater success can be expected if the corrosion and oxidation reactions are separated in the laboratory test.

Experimentally it was found that, even with oils of greatly varying corrosivities, the soluble metal concentrations in used lubricating oils from a test in a small gasoline engine of 50 hr duration did not depend upon the corrosivity of the oil. These concentrations fell in the ranges of 12 to 35 p.p.m. for copper and 40 to 80 p.p.m. for iron (estimated as metal) together with some dissolved lead soaps, which can be ignored as not possessing sufficient catalytic activity.[5] Taking everything into consideration, a catalyst composition of 20 p.p.m. Cu and 50 p.p.m. Fe, added as stearates, was chosen as typical of the catalytic conditions present in this particular engine test.

The oxygen absorption apparatus and experimental procedure for measuring oxidation stability have been described previously.[5] The oxidation temperature, which is not considered to be very critical in respect of the relative oxidation rates of the different oils, was chosen to be 150° C for experimental convenience. The 50-hr piston cleanliness test in a small single-cylinder air-cooled gasoline engine was designed to compare lubricating oils with respect to their tendency to form lacquer and carbon deposits on the piston at high operating temperatures.

The correlation given in Fig 1, between the times taken for the absorption of 20 ml of oxygen per gram of oil and the piston cleanliness rating, proved to be very good when examined statistically. From an inspection of the standard pistons used in laying out the rating scale, it was apparent that the amount of lacquer on the piston increased approximately exponentially as the cleanliness rating diminished. This fact accounts for the exponential form of the regression function, which is :—

$$\log_{10} R = -17{\cdot}32/t + 0{\cdot}8884$$

in which R is the piston cleanliness rating and t is the time in minutes for the absorption of 20 ml of oxygen per gram of oil.

The correlation coefficient is 0·917, which shows that a strong correlation exists between the oxygen absorption test and the engine test. On the other hand, the wide limits of $\pm 0{\cdot}16$ for the values of $\log_{10} R$ for 95 per cent confidence show that there are other operative factors not taken into account. This random scatter of results is no doubt partly due to the low reproducibility of the engine tests, which is also illustrated by the variation in the concentrations of the dissolved metallic compounds found in the lubricating oil. It may be concluded, therefore, that the oxidation test will provide a good prediction of whether an oil will perform well, moderately, or poorly in the engine test. It is even possible that the oxidation test, because of the better reproducibility obtained with it in comparison with the engine test, is more reliable than the engine test.

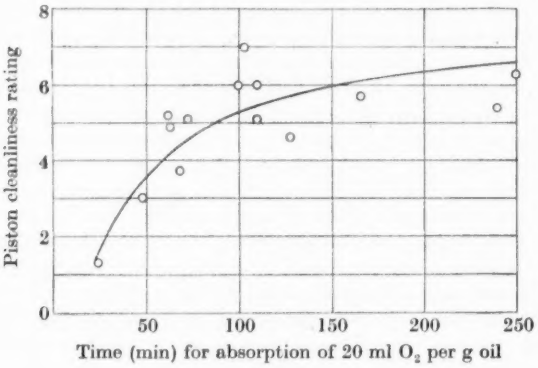

FIG 1

CORRELATION BETWEEN SMALL GASOLINE ENGINE RESULTS AND OXYGEN ABSORPTION TEST

However, it must be remembered that the catalytic conditions adopted for the oxidation test must be chosen to correspond as closely as possible to the catalytic conditions produced in the engine test with which correlation is being sought.

Lacquer Formation

In addition to determining the relationship between the capacity of an oil in the liquid state to react with oxygen and its piston lacquer forming tendency in an engine test, it is also possible to study directly in the laboratory the lacquer forming tendency of an oil. An apparatus with which this can be done consists of an inclined cast iron plate, maintained electrically at any desired temperature, over which oil continually flows and is re-circulated with a small pump. A similar apparatus has recently been described by McKee and Fritz.[6] Van der Minne (unpublished results) claims that it is essential to maintain an oil flow over the metal surface if the deposit is to resemble deposits formed in the hot areas of engines in respect of

solubility in solvents, and oxygen content. This is not achieved if the oil is allowed to dry up, as occurs in many similar test apparatuses.

Using this apparatus to study the formation of lacquer on the hot metal surface, particularly from the kinetic aspect, some very interesting results were obtained. Firstly, by scraping off and weighing the amount of lacquer formed in a given period of time, it was found that the rate of formation of lacquer at any given surface temperature remained constant with time. In other words, lacquer formation was linear with respect to time. It is therefore satisfactory to perform tests of fixed duration—20 hr being actually used—and to regard the average reaction rate over this period as the true rate. Secondly, it was found that the change in the rate of deposit formation with temperature does not obey the Arrhenius equation throughout the temperature ranges investigated, but that deposit formation appears to commence quite suddenly when the temperature rises to a certain fairly narrow critical region.

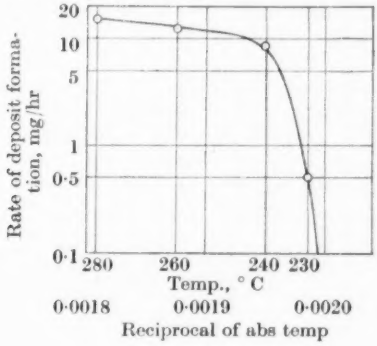

FIG 2

DEVIATION OF HOT PLATE TEST RESULTS FROM ARRHENIUS' LAW

Fig 2 shows the relationship between the logarithm of the rate of deposit formation and the reciprocal of the absolute temperature. If the Arrhenius equation was obeyed a straight line would be obtained, the slope of which gives the activation energy of the reaction. It is probable that at high temperatures the Arrhenius equation does apply, in which case the activation energy of the deposition reaction of the oil described by Fig 2 over the temperature range 260° to 280° C becomes a mere 3 k.cal/g mole. This value is much lower than the activation energy for the liquid phase oxidation of the same oil, which was found to be between 30 and 40 k.cal/g mole from the results of oxygen absorption measurements.

For most lubricating oils tested on the hot plate the critical temperature for the onset of deposit formation is about 220° C, which corresponds to the temperature which is usually considered to be the limiting temperature for piston ring grooves, if high temperature ring-sticking due to lacquer formation from oil oxidation is to be avoided. When the reciprocal of the rate of deposit formation on the hot plate is plotted against temperature the form of curve obtained is that shown in Fig 3. It is perhaps significant that a similarly shaped curve was obtained for the variation of ring-

sticking time with temperature in an air cooled engine (also shown in Fig 3).

Rosen [7] has previously stressed the importance of temperature in performance of lubricating oils, and has stated that deposit formation only takes place within a fairly narrow temperature range. This conclusion is based on the results of coking tests made on metals subjected to a controlled heat gradient. It is possible that in Rosen's experiments the absence of deposits *above* his second critical limiting temperature was due to the volatilization of the oil before deposits could form. On the other hand, the absence of deposits above the second critical temperature may have been due to burning away of deposits. General support is also provided by the engine test results of Phillipovitch,[8] who, in similar engine tests to those from which the results in Fig 3 were obtained, found that with increasing temperature the ring-sticking time first decreased rapidly, due

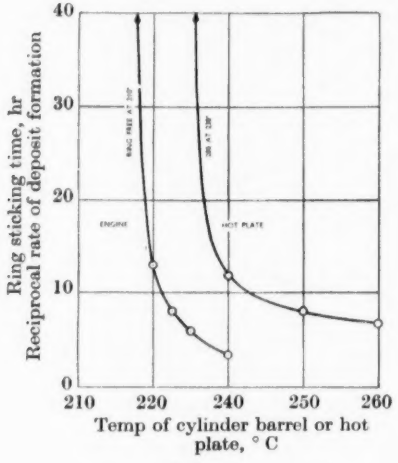

FIG 3

COMPARISON OF ENGINE RING STICKING RESULTS WITH HOT PLATE RESULTS

to the formation of "asphaltenes," then increased again because the "asphaltenes" were burnt off, and finally decreased once more as the result of rapid carbonization of the oil. It does not seem reasonable, however, to suppose that asphaltenes burn away at temperatures at which the oil remains unburnt and continues to provide good lubrication. It is felt that there must be some other explanation for the phenomena. Whether the freeing of the rings above the second critical temperature of Rosen and Phillipovitch, and the final seizure due to carbonization, are significant with regard to normal engine operation is perhaps questionable. On the other hand, there appears to be little doubt that until the first critical temperature is reached no ring-sticking due to lacquer formation from oil oxidation is likely to occur, but that as soon as this temperature is exceeded rapid ring-sticking is possible.

Proof that the lacquer itself is an oxidation product is afforded by the

fact that the lacquers produced in the hot plate test can be chemically reduced with concentrated hydriodic acid and red phosphorus in a Carius tube at 240° C to give good yields of oils of the same molecular weight as the original oils from which they were produced. This would not be likely if thermal cracking had occurred. Similarly, some deposits formed in engines can be chemically reduced to oils of the same molecular weight as those from which they were derived, although in the case of engine deposits the yields obtained are low, presumably because of the presence of combustion chamber " carbon."

The Influence of Soluble Oxidation Products

It has often been stated that beneficial properties develop in oils during use, one of the benefits claimed being an increase in oiliness. There is no doubt that surface-active material is produced by the oxidation of the oil as demonstrated by the lowering of the interfacial tension of the oil against water. In fact, van der Minne [9] has shown that oil oxidation " resins," which by his definition are the oxidation products soluble in oil and aromatic-free petroleum spirit, are active dispersing agents for the insoluble lacquers produced in engine operation, and in this respect he also found that they counteracted the effect of typical metallic compound additives of the dispersant type developed for use in lubricating oils. His observation indicated an unexpected similarity between colloidal phenomena in non-aqueous and aqueous media, and established that oil oxidation products could exert a pronounced peptizing action on dispersions of carbonaceous matter in oils.

Confirmation of the dispersing properties of oil oxidation products is given by the following results obtained from sedimentation experiments. These were carried out in a stoppered IP steam emulsion test tube, into which were introduced 4 g of carbon black and 40 ml of petroleum ether. The tube was shaken vigorously under standardized conditions in a mechanical shaker, and the time for the surface of the carbon layer to settle from the 30- to the 20-ml marks was noted. A sample of oil was weighed in, and the shaking and settling was repeated. This was repeated to obtain a plot of the increase in settling time against the weight of oil added, and the Peptization Rating of the oil was defined as the percentage increase in settling time per gram of added oil.

As may be seen from Table I, the Peptization Rating of an unused

Table I

Peptization Ratings of Base Oils and Additive Oils

Base oil A	59
Base oil A after use in engine and filtration	170
Base oil A + additive to H.D. standards	320
Base oil B	60
Base oil B oxidized in laboratory	12,600
Base oil B + 2% w of acetone insoluble substances from oxidized oil B	620

straight mineral oil is appreciably lower than that of a filtered used oil, and the latter is more than half of the Peptization Rating of a typical oil

of the heavy duty class containing a dispersant additive. Laboratory oxidation produces a marked increase in the Peptization Rating, which increases with the extent of oxidation. Use in an engine and laboratory oxidation increases the viscosity of the oil, but by comparing unused oils differing only in viscosity it was found that the influence of viscosity alone was negligible.

Since the oxidation products of hydrocarbon lubricating oils consist of a complex mixture of substances, widely varying in chemical structure and molecular size, it was considered feasible that some of these oxidation products might be more effective dispersants than others. Laboratory-oxidized Base oil B, which as given in Table I, had a Peptization Rating of 12,600, was therefore chromatographically separated into fractions of different surface activities, using kieselguhr as the adsorbent and a range of solvents of differing polarity as eluants. The results confirmed the view that the oxidation products could be separated into fractions of different surface activities. Using a magnesia column, and *iso*pentane, benzene, ether, and acetone as eluants in that order, it was found that the most active fraction was that left on the magnesia after elution. This fraction was recovered by dissolving the magnesia in aqueous acetic acid and separating the oxidation products by petroleum ether extraction. It had a Peptization Rating of 50,000.

An alternative method of separating a highly active fraction from the oxidized oil was by continuous extraction with hot acetone, in which all the oxidized oil except the most active material is soluble. The acetone-insoluble fraction obtained in this way was freely soluble in hydrocarbons, was neutral in chemical reaction, and possessed a Peptization Rating of 45,000.

In addition to exhibiting a strong activity in the carbon sedimentation test, this acetone-insoluble fraction also showed a pronounced ability to prevent sludging in a high temperature laboratory sludging test which was developed to correlate more closely with engine performance than the sedimentation test. In this sludging test, using the same apparatus as in the lacquer deposition test, a standard used lubricating oil is allowed to flow over a heated metal plate maintained at 200° C, which is lower than the critical temperature for the formation of lacquer as described earlier, and the amount of oil-insolubles which adheres to the surface of the plate in an hour is measured. The standard used oil was obtained from an engine operating under normal conditions, and had only been mildly oxidized in use. The addition of 2% w of the acetone-insoluble fraction reduced the deposition of oil-insolubles in this test to a negligible amount, and the effect produced was equivalent to that obtained with a normal amount of a typical metallic compound dispersant additive, as developed for use in heavy duty oils.

The acetone-insoluble fraction also raised the critical temperature for lacquer formation of a typical solvent refined high V.I. oil in the hot plate test, which again is probably a result of its dispersant properties.

Various engine tests were carried out on a 2% w solution of the acetone-insoluble fraction in a typical solvent refined high V.I. lubricating oil, and the results are compared in Table II with those obtained for the same oil containing a conventional additive of the metallic compound type.

These results indicate clearly that the acetone-insoluble fraction of the oxidized lubricating oil possesses dispersant properties of the same degree as those possessed by metallic compound additives of the dispersant type.

TABLE II

The Influence of the Acetone-insoluble Fraction on Engine Performance

Type of test	Solvent refined high V.I. base oil	Oil + 2% w acetone-insolubles fraction	Oil + metallic compound additive
16 hr high temperature gasoline engine measuring oxidation stability (piston cleanliness rating *)	4·8	4·3	7–10
Gasoline engine sludging test (valve gear rating *) . .	0	4	6–8
Diesel engine piston cleanliness test measuring detergency (piston cleanliness rating *) . .	4·5	5	6·5–9
Diesel engine ring sticking test measuring chiefly detergency (ring-sticking time) . .	2 hr	6 hr	10 hr

* Ratings: 10 = clean and 0 = completely dirty.

DISCUSSION

The evidence presented in this paper shows that oxidation of the lubricating oil can lead to both deterimental and beneficial results in engine performance. Oxidation of the lubricating oil may lead to deposition of lacquer on certain engine parts, but this should not be taken to imply that lacquer cannot also be formed from the fuel. As far as lacquer derived from the lubricating oil is concerned, however, it appears that it may be deposited by two distinct mechanisms. There is a general lacquer deposition on the hot parts of the engine, and the amount of lacquer formed by this mechanism is probably proportional to the extent of oxidation of the oil. It is believed that this lacquer depositing process is usually slow and causes few difficulties in engine operation. The other lacquer depositing process is very rapid, and occurs when the piston temperature rises above a critical value. The rapid accumulation of deposits by this process quickly leads to stuck piston rings. However, when this second process does not occur, it should be possible to predict the piston lacquering tendency of an oil from its oxidation stability measured in the laboratory oxygen absorption test, provided that the appropriate catalytic conditions are chosen.

From the low activation energy associated with the lacquer deposition process in the hot plate test it can be inferred that this process is probably controlled by an adsorption mechanism. This view receives support from the fact that the highly surface active material, namely the acetone-insoluble fraction of an oxidized lubricating oil, raises the critical lacquer deposition temperature. This result, which is confirmed by engine test data, and the other data given in Table II show that, whilst oxidation of the lubricating oil can result in the deposition of lacquer on engine parts, at the same time there are some substances produced by the oxidation of the

oil which have a beneficial effect on the performance of the oil. However, it should not be concluded that oxidation instability in itself is a desirable characteristic to be sought in making a lubricating oil. There are obviously many oxidation products which are undesirable, since they lead to lacquer formation, ring-sticking, and in extreme cases to the production of sludge and bearing corrosion. The acetone-insoluble fraction of an oxidized oil described in this paper typifies a class of hydrocarbon lubricating oil oxidation products which are non-corrosive, inhibit lacquer deposition, and disperse sludge. If a lubricating oil can be designed to produce by oxidation in the engine only this class of compound at a sufficient rate, there would be less need to introduce conventional additives, but one important function which the oxidation product cannot perform is to neutralize any acids entering the lubricating oil from the combustion chamber.

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THE KINETIC STUDY OF DETERIORATION IN USE OF I.C. ENGINE CRANKCASE OILS

By J. HUGHES * and J. B. MATTHEWS *

SUMMARY

Mathematical equations are derived which describe the kinetics of the deterioration of I.C. engine crankcase oils in its various aspects, such as the accumulation of oil-insolubles and soluble oil oxidation products and the depletion of additives. By the application of these equations it is shown how a closer understanding can be obtained of the mechanisms of oil deterioration. When applied to additive depletion the kinetic approach is shown to be useful in throwing light on the causes of additive depletion. In addition, the kinetic approach makes possible the calculation of the optimum additive concentrations required for specified engine operating conditions and of the maximum oil change periods. The kinetic approach to oil deterioration phenomena suggests how engine tests can be designed to give the maximum information.

SYMBOLS

A	Rate of formation in, or of entry into, the oil of the contaminant.
C_t	The concentration of the contaminant in the oil after use for time t.
$\bar{C}$	Average concentration of the contaminant during the period t.
d_t	The concentration of fuel diluent in the oil after use for time t.
d	The average concentration of fuel diluent in the oil during the period t.
δ	Amount of additive destroyed expressed as the total amount of additive lost at time t per unit quantity of initial oil charge.
E	Identical with $(X_m - X_0)$.
e	Base to Naperian logarithms.
k	The constant relating rate of sludge deposition to concentration of oil-insolubles.
k_0	Zero order additive destruction rate constant.
k_1	First order additive destruction rate constant.
q	The quantity of contaminant formed in, or entering into, unit quantity of oil in the period t.
R_1	Rate of oil consumption.
R_m	Rate of oil make-up.
r_1	Rate of consumption of oil or oil plus fuel diluent per unit quantity of oil or oi plus fuel diluent in the system.
r_m	Measured rate of oil make-up per unit quantity of oil.
S	Total amount of sludge deposited in engine in period t.
t	Period of operation of engine.
Δt	Very short time interval in the operation of the engine.
W_0	Total quantity of oil in engine initially.
W_t	Amount of oil plus fuel diluent in engine after period t.
X	Additive concentration.
X_t	Additive concentration at time t.
X_0	Initial additive concentration.
X_m	Additive concentration in make-up oil.
$\bar{X}$	Average additive concentration during period t.
ΔX	Decrease in additive concentration in short time interval Δt.

INTRODUCTION

IN a previous paper [1] conclusions have been reached concerning the nature of the deterioration which a lubricating oil undergoes in an internal combustion engine. The complete study of the mechanism of deterioration of the lubricating oil during engine operation, however, requires a knowledge, not only of the end-products of the oil deterioration process, but also of the

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kinetics of this process. The kinetic study of the oil deterioration process can be compared to the kinetic study of a chemical reaction occurring in an isolated system, but it is necessary to allow for the fact that the oil in the engine is being consumed during the experiment, and, usually, fresh oil is added to the system in the form of " make-up " oil at intervals during the experiment. The problem is, in fact, analogous to the investigation of the kinetics of a chemical reaction in a leaking reaction vessel.

Under normal engine operating conditions the rate of oil consumption varies, and no special effort is made to maintain constant the total amount of oil in the engine. In these circumstances only approximate corrections for oil consumption and the addition of make-up oil can be applied. In controlled laboratory engines, however, the oil consumption rate can be kept constant. The total quantity of oil in the engine will then decrease at a constant rate, or, alternatively, this quantity may be kept constant by additions of fresh oil. In both cases it is possible to introduce corrections to enable the kinetics of the deterioration process to be calculated from the analytical data for the used oil, measured as a function of the engine operating time.

In the previous paper [1] the theory of oil deterioration given is that insoluble particles (constituting the solid phase in the exhaust smoke) enter the lubricating oil, from which they adsorb oxidation products and other surface active matter. In this paper the kinetics of the contamination process are dealt with, and it is shown how a kinetic treatment of another important aspect of oil deterioration, namely additive depletion, can provide useful information on the mechanisms involved and also on the initial additive concentrations and oil change periods necessary to maintain efficient operation.

General Kinetic Treatment

The most simple case for kinetic treatment is that in which the contaminant enters or is formed in the oil at a constant rate. The relationship between contaminant concentration and time under these conditions has already been derived by C. A. Bouman,[2] who assumed that the oil-insolubles entered the oil at a constant rate, the oil was consumed at a constant rate, make-up oil was added continuously to keep the oil charge constant, and there was no deposition of oil-insolubles on engine parts. With these assumptions Bouman derived the equation :—

$$C_t = \left\{1 - e^{-\frac{R_1 t}{W_0}}\right\} \frac{A}{R_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in which C_t is the concentration of the contaminant in the oil after time t, W_0 is the quantity of oil present in the engine, A is the rate of formation in or of entry into the oil of the contaminant, and R_1 is the rate of oil consumption.

This equation shows that the limiting value for the contaminant concentration, reached only after infinite time, is A/R_1, the ratio of the contamination rate to the oil consumption rate. It also shows that when $t = W_0/R_1$, *i.e.*, when the total oil consumed equals the initial charge, then the contaminant concentration will reach 63·2 per cent of the limiting value.

Equation (1) is in some cases very useful in interpreting the data obtained from used oil analysis, but it is very limited in scope. For this reason a more general kinetic treatment has been developed in which no assumption is made about the rate of formation of contaminants, and allowance is made for the effects produced by the dilution of the oil by fuel. Thus, of the assumptions made by Bouman only one is now retained, namely that the rate of oil consumption is constant.

With Addition of Make-up Oil

In this case, in which the total quantity of oil is kept constant by frequent additions of make-up oil,

$$C_t = q - r_1 t\bar{C} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

in which $\bar{C}$ is the average concentration of the contaminant from zero time to time t, r_1 is the rate of oil consumption per unit quantity of oil in the system, and q is the quantity of contaminant formed in or entering into unit quantity of oil in the system in time t.

Now, C_t can be any function of t, and therefore it follows that :—

$$\bar{C} = \frac{1}{t}\int_0^t f(t)dt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Although $f(t)$ is known only in special cases, $\int_0^t f(t)\,dt$ can be obtained graphically, being the area included between the experimental C_t versus t curve and the time axis. Values of $\bar{C}$ can, therefore, be calculated from equation (3), and when fuel dilution is negligible r_1 is equal to r_m, the measured rate of oil make-up per unit quantity of oil in the system.

By substituting in equation (2) it is possible to obtain the relationship between q and t.

When fuel dilution cannot be neglected, since the total amount of oil plus fuel lost from the system must equal the total amount of oil plus fuel added,

$$r_1 t = r_m t + d_t + dr_1 t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

in which d_t is the concentration of diluent in the oil at the end of time t, and $\bar{d}$ is the average concentration of diluent in the oil from zero time to time t, and r_1 now denotes the rate of loss of the oil plus fuel mixture. Thus,

$$r_1 = \frac{r_m t + d_t}{t(1 - \bar{d})} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

combining equations (2) and (5)

$$q = C_t + \frac{r_m t + d_t}{(1 - \bar{d})}\bar{C} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

In order to find values of q from equation (6) it is necessary to know the appropriate values of d. These can be obtained graphically from the measured variation of the fuel diluent with time. All the necessary data are then available to give the time dependence of q.

When the contaminant is lost from the oil by some other mechanism, *e.g.*, sludge deposition if the contaminant is the oil-insolubles, this factor can be taken into account by modifying r_m. Thus, if sludge deposition occurs and its rate is proportional to the concentration of oil-insolubles, in the application of equation (6) to the oil-insolubles r_m should be replaced by $r_m + k$, where k is the constant relating the rate of deposition to concentration of oil-insolubles. The value of k is given by :—

$$k = \frac{S}{W_0 t C} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

in which S is the total amount of sludge deposited in the engine in time t. If the amount of sludge cannot be measured, and hence no allowance for sludging can be made, the values obtained for q are, of course, the net values of the concentration of oil-insolubles remaining in suspension.

Two illustrations of the application of the above treatment are given.

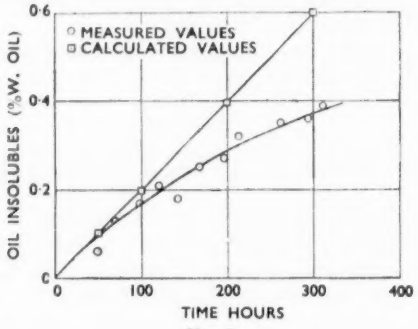

FIG 1

CHANGE OF CONCENTRATION OF OIL-INSOLUBLES WITH ENGINE OPERATING TIME

First, consider the production of oil-insolubles in a test with a single-cylinder high-speed diesel engine. In this engine test operating conditions were kept constant, and the quantity of oil in the engine was also maintained approximately constant by frequent small additions of make-up oil. The used oil was analysed at frequent intervals by the methods already described.[1]

Fig 1 shows the change of the observed oil-insolubles concentration with the period of engine operation. This curve was used to obtain the data shown in Table I, fuel dilution in this case being negligible (<1 per cent).

The q values in Table I, which are also plotted in Fig 1, show quite conclusively that the oil-insolubles entered the oil, or were formed in it, at a constant rate. This conclusion could not have been reached from direct inspection of the analytical data.

Secondly, consider the production of oil-soluble contaminants in the lubricating oil during a test in the same single-cylinder diesel engine on a lightly refined oil of low V.I.

Fuel dilution was again negligible, and this simplifies the calculations, and the curves describing the measured and the calculated time-dependence of

TABLE I

Data for Obtaining the True Rate of Production of Oil-insolubles

Engine Operating Conditions :

$W_0 = 7700$ g, $R_m = R_1 = 25{\cdot}6$ g/hr; test duration = 312 hr. Hence $r_1 = 0{\cdot}0033$ hr^{-1}

t (hr)	C_t smoothed (%w)	$\int_0^t f(t)\,dt$ (%w × hr)	$\bar{C}$ (%w)	q (%w)
0	0	0	0	0
50	0·096	2·7	0·054	0·105
100	0·167	9·2	0·092	0·198
200	0·287	32·2	0·166	0·398
300	0·371	75·7	0·252	0·600

the concentration of oil-soluble contaminant are given in Fig 2, the relevant data being shown in Table II. It is obvious that the true rate of production of the oil-soluble contaminants is not independent of time.

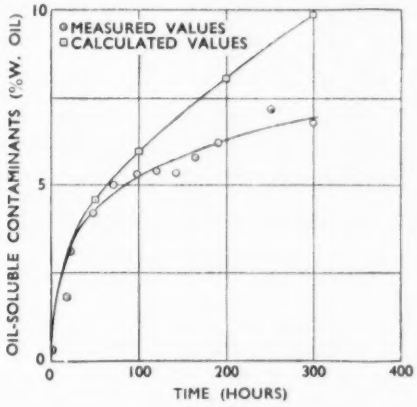

FIG 2

CHANGE OF CONCENTRATION OF OIL-SOLUBLE CONTAMINANTS WITH ENGINE OPERATING TIME

With no Addition of Make-up Oil

If no make-up oil is added the treatment would be as follows. Putting W_t as the amount of oil plus fuel diluent remaining in the engine after time t,

$$\left\{\frac{W_0 q - R_1 t C}{W_t}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

But,

$$R_1 t = W_0 - W_t + d_t W_t + d R_1 t \quad . \quad . \quad . \quad . \quad (9)$$

and therefore :—

$$R_1 = \frac{W_0 - W_t + d_t W_t}{t(1 - \bar{d})} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Combining (8) and (10) and re-arranging :—

$$q = C_t \frac{W_t}{W_0} + \bar{C} \left\{ \frac{1 - \frac{W_t}{W_0}(1 - d_t)}{(1 - \bar{d})} \right\} \quad . \quad . \quad . \quad (11)$$

All the terms on the right-hand side of equation (11) can be measured, and therefore, the time dependence of q can be obtained.

TABLE II

Data for Obtaining the True Rate of Production of Oil-soluble Contaminants

Engine Operating Conditions :
$W_0 = 7950$ g, $R_m = R_1 = 14$ g/hr; test duration = 300 hr. Hence $r_1 = 0{\cdot}0018$ hr^{-1}

t (hr)	C_t smoothed (%w)	$\int_0^t f(t)\,dt$ (%w × hr)	$\bar{C}$ (%w)	q (%w)
0	0	0	0	0
50	4·3	156	3·1	4·58
100	5·25	399	4·0	5·97
200	6·3	979	4·9	8·06
300	6·95	1619	5·4	9·87

When fuel dilution is negligible equation (11) reduces to :—

$$q = C_t \frac{W_t}{W_0} + \bar{C}\left(1 - \frac{W_t}{W_0}\right) \quad . \quad . \quad . \quad . \quad . \quad (12)$$

or

$$q = \frac{C_t W_t + \bar{C} R_1 t}{W_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Allowance for sludge deposition can be made as previously, *i.e.*, R_1 in equation (7) may be replaced by $(R_1 + k)$ or q is defined as the net quantity remaining in suspension.

THE KINETICS OF ADDITIVE DEPLETION

The important subject of additive depletion can be usefully studied from the kinetic approach by essentially the same methods as those already discussed in relation to contaminants. Assumptions can be made concerning the mechanism of the destruction of the additive, and, on the basis of these assumptions, the actual concentrations of the additive remaining in the used oil can be calculated as a function of time. If these values agree with the measured values, the assumptions are confirmed. Alternatively, the measured concentration versus time curve may be corrected for

oil consumption and fuel dilution to give the true rate of additive destruction, from which deductions can be made concerning the mechanism of destruction. The latter method is more useful in testing analytical data, but the former is very useful in studying the economics of additive consumption.

In chemical kinetics we speak of the order of the chemical reaction. Thus, if the rate of the chemical reaction is independent of the concentration of a reactant, it is said to be of zero order with respect to that reactant. On the other hand, if the rate of the reaction is proportional to the concentration of a reactant, the reaction is said to be a first order reaction with respect to that reactant. By analogy we may speak of zero order and first order additive destruction processes, when the rate of destruction is either independent of, or proportional to, the additive concentration. The kinetics for such processes of additive destruction are given below.

Zero Order Additive Destruction

Assuming that the rate of oil consumption is constant, that the total oil quantity is maintained constant by frequent additions of make-up oil, that fuel dilution can be neglected, and that the additive is destroyed by a process of zero order, then

$$\Delta X = -k_0 \Delta t - r_1 \Delta t X_t + r_m \Delta t X_m \quad . \quad . \quad . \quad . \quad (14)$$

in which X_m is the additive concentration in the make-up oil, X_t is the additive concentration after time t, ΔX the change in additive concentration over the short time interval from t to $(t + \Delta t)$, and k_0 the rate of the zero order destruction process.

Since, according to the assumptions, r_1 is equal to r_m, then :—

$$\Delta X = -r_m \Delta t \left(\frac{k_0}{r_m} + X_t - X_m \right) \quad . \quad . \quad . \quad . \quad (15)$$

On putting this in the integral form :—

$$In \left(\frac{k_0}{r_m} + X_t - X_m \right) = 1n \left(\frac{k_0}{r_m} - E \right) - r_m t \quad . \quad . \quad (16)$$

in which $E = (X_m - X_0)$ denotes the excess of the additive concentration in the make-up oil over the initial concentration X_0.

By re-arrangement :—

$$X_t = X_m - \frac{k_0}{r_m} (1 - e^{-r_m t}) - E e^{-r_m t} \quad . \quad . \quad . \quad (17)$$

This equation gives the change of additive concentration with time under the assumed conditions. Of much more frequent use is the special case of equation (17) when $X_m = X_0$, which is :—

$$X_t = X_0 - \frac{k_0}{r_m} (1 - e^{-r_m t}) \quad . \quad . \quad . \quad . \quad . \quad (18)$$

From equation (18) the limiting value of the additive concentration is :—

$$X_\infty = X_0 - \frac{k_0}{r_m} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

In other words, the total decrease in additive concentrations which can occur under these conditions is independent of the initial additive concentration, and depends only on the ratio of the depletion rate to the oil consumption rate.

First Order Additive Depletion

With the same assumptions as before, then :—

$$\Delta X = -k_1 \Delta t X_t - r_1 \Delta t X_t + r_m \Delta t X_m \quad . \quad . \quad . \quad (20)$$

in which k_1 is the rate constant of the first order depletion process. When r_m is equal to r_1 :—

$$\Delta X = -(r_m + k_1)\left(X_t - \frac{r_m X_m}{r_m + k_1}\right)\Delta t \quad . \quad . \quad . \quad (21)$$

When this is put in the integral form :—

$$X_t = \frac{r_m X_m}{r_m + k_1} + \frac{X_0 k_1 - r_m E}{r_m + k_1} e^{-(r_m + k_1)t} \quad . \quad . \quad . \quad (22)$$

In the more usual case, when X_m is equal to X_0, equation (22) becomes :—

$$X_t = X_0 \left\{ \frac{r_m}{r_m + k_1} + \frac{k_1}{r_m + k_1} e^{-(r_m + k_1)t} \right\} . \quad . \quad . \quad (23)$$

The limiting value of the additive concentration in this case is :—

$$X_\infty = \frac{r_m}{r_m + k_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

The maximum decrease in additive concentration under these conditions is directly proportional to the initial additive concentration.

From equation (18) it follows that, if identical tests are run under constant operating conditions using two different initial additive concentrations, the total decrease in additive concentration will be the same in each case for any given value of t, when the destruction process is of zero order. On the other hand, from equation (23), in the case of a first order destruction process the ratio of the additive concentrations at any time t will be equal to the ratio of the initial additive concentrations. These conclusions are illustrated graphically in Figs 3 and 4.

It is, however, laborious to run identical tests at different additive concentrations in order to determine the order of the destruction process. For this reason, the alternative approach of obtaining the true rate of destruction by making appropriate calculations from the measured data, and drawing conclusions from this calculated rate of destruction about the mechanism of destruction, is normally preferred. In the latter method no assumption is made concerning the order of the destruction process, and the treatment is as follows.

Treatment Adopted when the Order of Destruction Process is Unknown

When the quantity of oil is kept constant by frequent additions of make-up oil :—

$$\delta = X_0 - X_t + r_m t X_m - r_1 t \bar{X} \quad . \quad . \quad . \quad . \quad (25)$$

in which δ is the amount of additive destroyed expressed as the total amount of additive lost at time t per unit quantity of the initial oil charge, and $\bar{X}$ is the average additive concentration during period t. The value $\bar{X}$

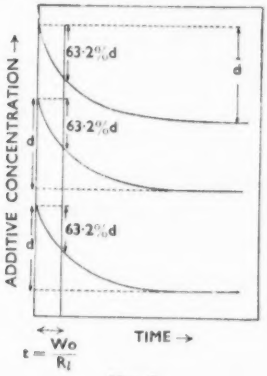

FIG 3

VARIATION OF ADDITIVE CONCENTRATION WITH TIME
ZERO-ORDER ADDITIVE DESTRUCTION

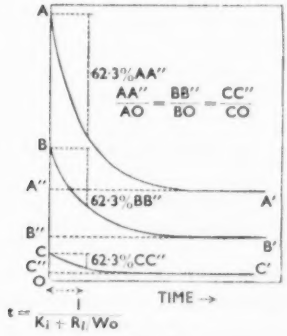

FIG 4

CHANGE OF ADDITIVE CONCENTRATION WITH TIME
FIRST-ORDER ADDITIVE DESTRUCTION

may be found graphically, and, if fuel dilution is negligible, r_m is equal to r_1. When fuel dilution cannot be neglected, substitution of equation (5) into equation (25), gives :—

$$\delta = X_0 - X_t + r_m t X_m - \bar{X} \frac{r_m t + d_t}{(1 - d)} \quad . \quad . \quad . \quad (26)$$

The values of d_t and $\bar{d}$ are found from the experimentally established variation of fuel concentration with time.

When no make-up oil is added, then :—

$$X_t = \frac{X_0 W_0 - \delta W_0 - R_1 t \bar{X}}{W_t} \quad . \quad . \quad . \quad . \quad . \quad (27)$$

By substituting for R_1 from equation (10) :—

$$\delta = X_0 - X_t \frac{W_t}{W_0} - \bar{X} \left\{ \frac{1 - \frac{W_t}{W_0}(1 - d_t)}{(1 - \bar{d})} \right\} \quad . \quad . \quad (28)$$

When fuel dilution is negligible :—

$$\delta = X_0 - \frac{X_t W_t + \bar{X} R_1 t}{W_0} \quad . \quad . \quad . \quad . \quad . \quad (29)$$

By applying the appropriate equation for δ to the experimental data of a single test the true rate of destruction curve, by which is meant the curve which would have been measured if oil consumption was nil, can be

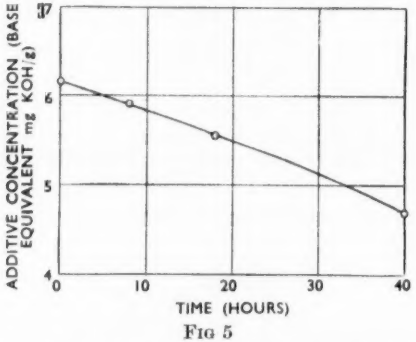

FIG 5

CHANGE OF ADDITIVE CONCENTRATION WITH ENGINE OPERATING TIME

obtained. From the form of this curve the order of the destruction process can be deduced, and this should lead to a better understanding of the destruction mechanism.

An illustration of the application of the above treatment is provided by the additive depletion occurring in a test in a high-speed diesel engine (of different make from that previously used), which was run under constant operating conditions. The test was of short duration, and no make-up oil was added.

Additive concentration was measured as its base equivalent expressed in mg of KOH per gram of oil. Fig 5 shows the curve relating the observed additive concentration to test duration, from which the data shown in Table III were obtained. Fuel dilution was negligible.

Fig 6 which gives the relationship between δ and t, shows that the additive destruction process was of zero order with respect to additive concentration, the rate constant k_0 being 0·0325 mg KOH/g hour. These

TABLE III

Data for Obtaining the True Rate of Destruction of Additive in an Engine Test

Engine Operating Conditions :

$W_0 = 3400$ g, $r_1 = 17$ g/hr, $R_m = 0$.

t (hr)	X_t smoothed (%w)	$\overline{X}$ (%w)	W (g)	δ (%w)
0	6·16	—	3400	—
10	5·83	6·00	3230	0·32
20	5·49	5·83	3060	0·64
30	5·12	5·65	2890	0·97
40	4·70	5·46	2720	1·30

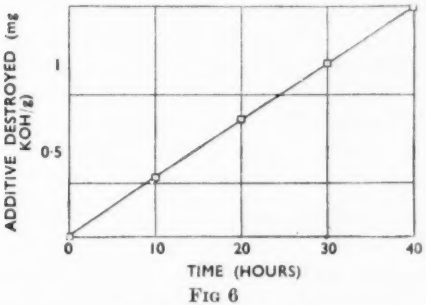

FIG 6

ADDITIVE DESTRUCTION RATE CURVE

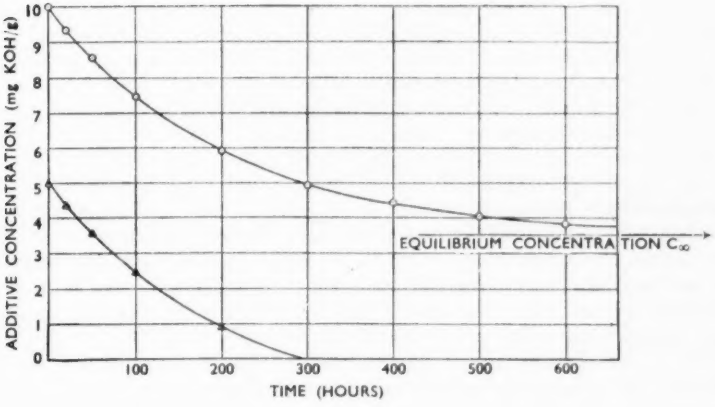

FIG 7

CALCULATED DEPLETION CURVES FOR DIFFERENT INITIAL ADDITIVE CONCENTRATIONS UNDER ENGINE TEST C OPERATING CONDITIONS

two parameters, the process order and its rate constant, are the only ones which can define adequately the destruction process, and they can be used to compare the performances of different additives or the severities of different operating conditions.

Furthermore, equation (18) can also be used to predict the course of additive depletion in this engine under different conditions. For example, when the total quantity of oil in the engine is kept constant by additions of make-up oil, other things being equal, the depletion curves for an oil with initial additive concentrations equivalent to 5 and 10 mg KOH per gram of oil, according to equation (18), are those given in Fig 7. Since the destruction process is of zero order with respect to additive concentration, the two curves are parallel, and in the case of the low initial additive concentration complete depletion occurs in 292 hr. The maximum depletion which can occur is a decrease in additive concentration equivalent to 6·5 mg KOH per gram of oil. If the minimum additive level required for satisfactory engine operation is known, these curves can be used to calculate the minimum initial additive concentration required to ensure an adequate additive concentration at all times, even in the case in which the oil is never changed. Alternatively, when the initial additive concentration is known, the maximum oil drain periods to maintain a satisfactory additive concentration can be calculated.

Discussion

Analytical data on used oil samples can sometimes give an erroneous impression of the chemical and physical processes occurring in the engine oil. This is because the real rates of oil deterioration may be masked by the effects of oil consumption, and also to some extent by dilution of the oils with unburnt fuel. The mathematical treatments given in this paper have shown how the true oil deterioration rates, defined as the measured rates corrected for oil consumption and make-up, may be found from the measured data. The true oil deterioration rate curves naturally afford a more reliable basis from which to deduce the mechanism of the oil deterioration process than do the observed curves. For example, the observed curve shown in Fig 1, in which the concentration of oil-insolubles increases to a limiting value, is typical of the sort of result obtained when the concentration of oil-insolubles is plotted against engine operating time. From the general shape of this curve it has been deduced previously [3] that lubricating oils have a certain holding capacity for oil-insolubles, and that when the concentration of oil-insolubles reaches the limit which the oil can hold in suspension deposition of the insolubles in the form of sludge commences. On the other hand, the kinetic treatment of the experimental data, as described now, shows that the flattening-off of the curve need have no connexion with sludge deposition, and in fact in the particular engine test dealt with in this paper sludge deposition did not occur, as confirmed by examination of the engine at the conclusion of the test, although a flattening-off of the observed oil-insolubles concentration–time curve was obtained.

In the case of additive depletion the example given illustrates how engine test data, if obtained under properly controlled conditions, can be used to determine the minimum concentration of additive which is required in the

fresh oil. In addition, the maximum oil drain periods can be calculated, provided that the minimum additive concentration necessary for good performance is known. These limiting concentrations and oil drain periods will vary with the engine operating conditions, and with other factors, such as the fuel. Nevertheless, by obtaining data for a wide range of operating conditions and fuels it should be possible to determine the optimum additive concentration and oil drain period.

It seems reasonable to conclude that, in order to obtain the fullest information from engine tests, they should be planned so that the analytical data for the used oil can be treated kinetically along the lines indicated in this paper. The conditions which should be aimed at in designing the engine tests should be as follows :—

(1) Constant engine operating conditions should be maintained. If a cycling procedure has to be used, samples should be removed each time at the same point in the cycle.

(2) The initial quantity of oil in the engine must be accurately measured. For short duration tests no make-up oil should be added, but the final quantity of oil left in the engine should be measured accurately. For long duration tests make-up oil should be added preferably by drip feed, or alternatively in small discrete amounts, so that the maximum fluctuation of the oil content is less than 10 per cent. The total quantity of make-up oil added should be accurately measured.

(3) Frequent samples should be removed for analysis. These should be small (<5 per cent of total oil charge), and for calculation they should be included in the oil-consumption.

(4) In additive depletion tests the final decrease in additive concentration should be high, *i.e.*, over 50 per cent, otherwise it may be difficult to distinguish between first and zero order processes. With engine or operating conditions which give low depletion rates a suitable decrease in additive concentration during the test may sometimes be achieved by adding as make-up oil an oil containing no additive.

Under these conditions, and with the application of the appropriate kinetic treatment to the used oil analytical data, it should be possible to use engines as research instruments in studying the deterioration processes in oils in considerable detail.

Acknowledgments

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[1] Matthews, J. B. *J. Inst. Petrol.*, 1953, **39**, 430.
[2] Bouman, C. A. "Properties of Lubricating Oils and Engine Deposits." 1950. (London : Macmillan and Co. Ltd.)
[3] Georgi, C. W. "Motor Oils and Engine Lubrication," 1950. Pp. 312–13. (New York : Reinhold Publishing Corpn.)

Discussion

P. W. L. Gossling: Referring to the mathematical study of additive depletion, I was sorry that only one actual example is given. This is for an engine which was found to be operating with zero order additive depletion. If there are, in fact, processes of depletion governed by first order considerations, as well as those of zero order, it would be extremely unlikely that other than mixed order additive depletion would generally apply, and I would ask the authors whether mathematical analysis can be applied usefully in such cases. Alternatively, I wonder if the authors conclude by inference that additive depletion is generally of zero order, the rate being controlled by an external process occurring at a constant rate, such as the entry of soot from the combustion space. Obviously, one example would be insufficient to allow such a conclusion to be drawn.

I would, in any case, point out that even the one example given does not conform with requirement (4), given on p. 475, as being desirable for this study. The additive destruction in 40 hours is only 24 per cent as against the desired 50 per cent or more postulated. In my view, the derived curves of Fig 7 are tantamount to an undue measure of extrapolation.

The third paper is of particular interest. I still think that laboratory oxidation tests in glass apparatus will ultimately be capable of superseding engine tests, not only because of the higher degree of standardization of conditions, but because they could be chosen to cover the conditions existing in a number of engines, even though by a series of tests. For electrical oils, it has for some time been recognized that to seek the simulation of operational variables in laboratory tests in vitro is a vain endeavour. These tests should be designed for the determination of types of oils expected to give the desired stability (see, for example, the approach of Massey in his 1952 papers to this Institute). Progress in the study of oxidation of electrical oils has been good, as a result of international collaboration. With engine oils, the stage of preoccupation with engine tests has doubtless been essential, and, admittedly, the task of designing oxidation tests has become very complicated by the introduction of additives.

The information that the soluble metal concentration in used engine oils after engine testing did not depend upon the corrosivity of the oil is most interesting. Possibly the soluble metal catalysts are produced largely by the action of acidic combustion products from the fuel. Mougey has stated * that the sulphur content of a fuel is the most important factor influencing oil oxidation and sludging, and, although the present authors dismiss the importance of lead as soaps, I should mention that Larsen *et al* stated † that leaded fuel greatly increased the oxidation rate of the oil, probably due to the reaction of the first-formed lead halides with iron to give iron halides, which were shown to be extremely highly pro-oxidant. Further, Burk *et al* pointed out ‡ that certain oils are particularly susceptible to the action of lead bromide. Admittedly, the introduction of heterogeneous catalysts tends to reduce the precision of tests, but it may be unwise to reject them at this stage.

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* *S.A.E. Jl*, 1945, 582.
† *S.A.E. Jl*, 1943, 316.
‡ *Industr. Engng Chem.* (*Anal.*), 1945, **17** (5), 302.

It would be interesting to know how the authors measured the corrosivity of the oil. Determinations of " existing " corrosivity of the used oil might not have much significance, since the most powerful corrosive agents are the volatile acids which may rapidly disappear, the controlling factor being the crankcase ventilation.

The evidence provided by the authors' hot plate test throws light on the mechanism of formation of the piston deposits. It seems that the lacquers may well be polymeric condensation products of the primary oxidation products formed, and the presence in oil solution of polymers of this type, but less highly oxidized, might account for the unexpectedly high viscosity-increase often obtained in tests with relatively low sump and high jacket-temperatures, although acidity and petroleum-ether-insolubles have not increased very much.

The isolation of the active acetone-insoluble oxidation product is most interesting, and I would like to know whether the authors have attempted to determine its chemical constitution. Also, what was the type of base oil B from which it was obtained? Table II on page 461, however, hardly bears out the authors' statement that the acetone-insoluble fraction possesses dispersant properties of the same degree as those of the metallic compound additive of dispersant type.

The paper on the distribution and colloidal behaviour of the insoluble particles is very convincing. Regarding the experimental side of the flocculation and settling tests, the part the oil itself may play, as distinct from additives, is not to be overlooked. In experiments using lamp-black some years ago, quite remarkable differences were found between unused mineral oils without additives. The oils were thoroughly mixed with 0·2 per cent of lamp-black and allowed to stand in test tubes for periodical observation of the degree of separation. With one low-viscosity neutral oil, the separation was complete in four days, while with a slightly lower viscosity oil, conventionally refined, and of high specific gravity, no visual separation was shown in three months. With a 500-viscosity conventionally refined oil, visual separation was nil in six months, but with a solvent-refined oil of a similar viscosity a good deal of separation was obtained in this time. These results are only typical of many, from which it was seen that viscosity was only of minor importance, and that, in general, naphthenic-type oils had the best dispersive powers. This was not universally true, however, and the method of refining probably played a significant part, dispersive power being possibly influenced by traces of polar compounds left behind from solvents used in refining processes.

In further work upon the effects of additives, a large number of tests was made, using a modification of the chromatographic detergency test of Talley and Larsen. While great increases in dispersive power result from addition of metallic detergents of the type commonly used, this was often greatly reduced by the addition of certain anti-oxidants, in particular certain phosphorus compounds, which may have a coagulating effect.

In the first paper were the conditions of each series of engine tests in Tables I and II constant, so that they can be considered to be standard engine tests on a series of oils? From a comment made in the second paper, this seems at least to have been the case for Oils 1 to 14 in Engine A. It would therefore have been interesting to have seen the respective end-of-

test engine sludge ratings for this series. An additional proof of the author's thesis would have been given if the engine sludge ratings had been found to be inverse to the final carbon contents of the oils. Assuming constant soot transfer to the oil side of the engine—and how otherwise can there be such a thing as a standard engine test?—the cleaner the engine, the dirtier the oil.

Table IV is very interesting. Rather than mere dependence of soot formation upon mixture strength as mentioned by the author, this data might equally well point to its dependence upon cylinder wall temperature, which has been usefully discussed by Broeze,* who also mentioned that soot deposition on the quartz windows of a special engine could be prevented by carefully drying the mixture, even one of rich petrol.

We are probably all agreed that the greater part of the carbon in used engine oils is derived from soot, but what of the author's rejection of the theory of Davies *et al*? The latter maintained that the insolubles included some carbon from the combustion zone, and in one test-run—for which they illustrated their results in their Fig 7—they showed that substantial naphtha-insolubles were produced in conjunction with very small amounts of chloroform-insolubles, which would include the soot. It is not known whether or not the insolubles reported in the main series of comparisons of used oils consisted largely of soot, because the authors did not report chloroform-insolubles against the naphtha-insolubles of their Fig 15, but it is known that their engine tests were reasonably severe, being Chevrolet tests run for approximately 83 hours with rather highly oxidizing conditions, as judged by the oil gallery temperature of 280° F. These conditions approach those pertaining to the L.4 test. I would ask the author whether the high-temperature conditions for Oils 24 to 34 were at all comparable in severity. All the remaining tests reported by the present author are for normal road operation or simulate such, and are therefore not at all comparable in severity of conditions with the L.4 test, so considerable oxidation would not be expected. Perhaps further discussion will lead to the acceptance of the very limited significance of the L.4 test, or of any other highly-accelerated engine tests in the assessment of oil for the so-called normal road-operation of petrol engines.

Dr L. Grunberg: The authors of the third paper seem to emphasize the catalytic action of dissolved copper and iron, and consider that the catalytic activity of solid surfaces is not of great importance in the deterioration of lubricating oils. This seems a rather sweeping generalization, and I suggest that, for instance, the decrease in the energy of activation in the formation of lacquer at about 220° C may be caused by an increase in the catalytic activity of iron surfaces covered by oxide.

We are, at present, studying the structure of oxide films which are formed when metal surfaces have been freshly disturbed. Roughly speaking, one finds two types of oxides. Those containing excess metal, such as zinc or cadmium oxide, which behave as donor semi-conductors, promote certain free radical reactions, and lead to the formation of hydrogen peroxide in the presence of water and oxygen. They can therefore be expected to act

* *Polyt. Tijdschr.*, 26 June 1951.

as catalysts in the deterioration of lubricating oils. Other oxides, containing excess oxygen, and behaving as acceptor semi-conductors, such as cuprous oxide, do not cause the formation of hydrogen peroxide, and therefore would not act as catalysts. Iron oxide occupies an intermediate position. Vernon *et al* have shown * that above 200° C iron oxide changes from an excess-oxygen to an excess-metal type of oxide. This seems to provide an explanation why increased lacquer-formation is observed in the van der Minne type of apparatus or in piston-ring grooves if the surface temperature exceeds 220° C. It also explains why Brook and Matthews found that, at lower temperatures, solid copper and iron are catalytically not very active. These workers were, of course, dealing not with the metals as such, but with the respective oxides, which under the conditions used, were of the excess-oxygen type. I can confirm, however, that a combination of copper and iron in solution promotes the uptake of oxygen very strongly. When copper is cut in a solution of a ferrous salt,† the oxidation to ferric ions is solely limited by the amount of oxygen present. It appears that dissolved copper transfers oxygen very easily to any oxidizable substance present.

I was glad to see that Drs Evans and Matthews have treated the examination of used lubricating oils as a problem in colloid chemistry. But they have not considered the influence of the acidity of the oil on the tendency of the carbon particles to flocculate. From experience with aqueous colloids, one would anticipate that acidity would play an important part. Some years ago I investigated suspensions of carbon black in oily media, and observed that the addition of traces of acetic acid caused sudden flocculation. With traces of oleic acid, flocculation was not as fast as with acetic acid, but one could observe a definite increase in the rate of flocculation.

I note that no viscometric measurements are reported in the papers. We are told that used lubricating oils are monodisperse systems, and that the concentrations of solid matter are relatively low. Under these circumstances, Einstein's equation for the viscosity of suspensions is undoubtedly applicable, and useful information might have been obtained from determinations of the viscosity ratios of unfiltered : filtered oil and of filtered : unused oil. The former would have provided a check on the percentage of oil-insolubles filtered off, and the latter would have yielded information about the changes which may have occurred in the oils themselves.

Another question is the mechanism of operation of detergent additives. I agree that the additive is adsorbed on the surface of the particles, and thus prevents flocculation. I wonder, however, whether the authors are aware of a recent paper by McBrian.‡ This gives a number of electron micrographs, which seem to show that, for proper operation, the additive itself should exist in the form of a very fine suspension, and not a solution. At Thorntonhall we are now using our electron microscope to check this hypothesis, and I should like to know the views of the authors on this matter.

Dr Matthews : With regard to Mr Gossling's queries concerning the

* *Proc. roy. Soc.*, 1953, **216A**, 375.
† Grunberg, L. *Proc. phys. Soc. Lond.*, 1953, **66B**, 153.
‡ McBrian, R., A.S.M.E. Preprint. Paper No. 52-A-40. 1952.

kinetics of additive depletion, the sole aim of our paper is to demonstrate how mathematics can be applied to engine test data. At present we cannot publish many of the experimental results obtained by this approach to the problems of additive depletion, but we can say that additive destruction processes corresponding to mixed orders, as well as to first order and zero order, have been observed. It is, of course, still possible to apply mathematical analysis usefully, even when the destruction process is of a mixed order. Thus, when the order of the process is known, it is necessary only to make some intelligent guesses in order to elucidate the actual mechanism of the destruction process which will fit the observed kinetics.

We found that dissolved lead compounds were relatively ineffective catalysts for the oxidation of the oil, in comparison with dissolved copper and iron compounds. In fact, of all the metallic compounds usually found in solution in used engine oils, only copper and iron compounds were found to be important as catalysts. The activity of the " crankcase catalyst " described by Larsen and co-workers was found by us * to be probably due to the oil-soluble iron contained in it.

Mr Brook will provide some information on the chemical constitution of the acetone-insoluble oxidation product which we found to be so effective as a dispersant additive. In this connexion, it is perhaps necessary to point out that the only performance data in Table II on p. 461 which are significant in respect of dispersant properties are those obtained in the gasoline engine sludging test. The other engine test data are included in this table in order to show that the addition of the oxidation product to the oil did not lower its performance in other respects, such as ring-sticking and piston cleanliness.

Concerning Mr Gossling's comments on the data in Tables I and II of the first paper, the majority of the oils described in these tables were taken from engines running under standardized conditions. Thus, all the oils in Table I, except 35 to 46, and in Table II, except 74 to 80, were obtained from controlled test engines (the excepted oils were taken from vehicles, or stationary engines operating under average conditions). However, the degree of control which can be exercised in test engines is far from ideal, and it is not possible to assume constant soot transfer to the oil side of the engine in the case of Oils 1 to 14, particularly since this engine test involved cycling conditions and rich fuel mixtures. Therefore, we cannot expect to find, nor did we find, any inverse relationship between engine sludge ratings and final carbon contents of the oil. On the other hand, eight of the oils in the group 1 to 14 are included in Fig 8 on p. 451 (the remaining six could not be included because the flocculation data were missing for these oils).

With regard to Mr Gossling's comments on Table IV of the first paper, cylinder wall temperature will influence the deposition of soot to some extent, but, on the other hand, it is necessary to produce the soot in the first place, and to do this in gasoline engines a rich mixture is necessary. For this reason, we incline to the view that the " carbon " content of the oils is more dependent on fuel mixture strength than on cylinder wall temperature.

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* Brook, J. H. T., and Mathews, J. B. *Disc. Faraday Soc.*, 1951 (10), 298.

The oil temperature conditions for Oils 24 to 34 were of about the same level as those obtained in the L.4 test, as also were the temperatures in the tests described in Tables V and VII. Under these abnormal conditions it is possible, as we have demonstrated, to get oxidation sludge of the type which was presumably obtained by Davies *et al.* All our evidence, however, indicates that this form of contamination will be extremely unlikely under normal operating conditions, and for this reason we must accept the conclusion that the L.4 test is of limited significance.

I am very interested in Dr Grunberg's suggested explanation of the critical temperature observed in the hot plate experiments. There may be some truth in this suggestion, but another possible explanation, which perhaps fits the facts better, involves the concept of critical temperatures for adsorption. Zisman in the U.S.A. has recently described experiments in which metals could be rendered oleophobic by being dipped into oils containing certain surface-active substances in solution. In these experiments, if a critical temperature is exceeded, the metallic surface no longer becomes oleophobic, but is readily wetted by the oil owing to desorption of the surface-active material, which at lower temperatures forms the oleophobic film on the metal. It is possible that a similar sort of mechanism is operating in the case of lacquer deposition. Thus, at temperatures lower than the critical temperature, perhaps the metal adsorbs substances from the oil solution which render the surface lacquer-phobic, but this film is desorbed above the critical temperature, and lacquer deposition can then proceed.

Although low molecular weight acids do have a tendency to cause flocculation in dispersions of carbon black, we do not know how significant this is in the case of used engine oils themselves. In any case, the important observation is that the deposition tendency of the oil-insoluble particles appears to be related to their colloidal behaviour, however this may be affected by the introduction into the system of additives or oil deterioration products.

We did initially carry out viscosity measurements on the used oils, before and after filtration. However, the experimental complications introduced by the fuel diluent rendered these measurements meaningless, and hence they were abandoned, and have not been reported here.

The results reported by McBrian, to which Dr Grunberg has referred, are very interesting, but so far we have not had an opportunity to examine his claims, and therefore we prefer not to comment on them at this stage.

MR BROOK : Mr Gossling has commented upon the fact that oils of different corrosivity have given similar dissolved metal concentrations in the used oil at the end of an engine test. This particular engine is not sensitive to corrosive oils, and the repeatability of the dissolution of metals is not good. The spread of results obtained when repeat tests are performed upon one oil is, in fact, so great as to mask any differences in the corrosivity of two oils. Although no measurements of corrosivity were made, in one test oil-soluble acids were added to the oil to ensure that it should be corrosive, but the dissolved metal concentrations at the end of the test proved to be very similar to those obtained without the addition of acids.

We have not considered the mechanism by which, in this particular

engine, metal becomes dissolved in the oil. For the purposes of using a laboratory oxidation test to simulate the engine test, it seems reasonable to regard 20 p.p.m. of copper and 50 p.p.m. of iron as fairly typical of the catalytic conditions in the engine, and thus to use these concentrations as the catalyst in the oxidation test. These considerations, applicable to this test, are not necessarily valid for all engine tests.

Different engine test results are obtained when a straight-run gasoline is substituted for the normal leaded fuel. In addition to the effects associated with the use of a halogen-containing scavenger, as mention by Mr Gossling, we know that the lead alters the course of combustion of gasoline, and some of the products of partial combustion of the gasoline may well be pro-oxidants for the lubricating oil. We therefore prefer not to take into account these complicating factors, as it is impossible to reproduce them in a simple laboratory test. No doubt, some of the scatter in our curve correlating the laboratory oxidation test with the engine test can be attributed to this.

Mr Gossling further enquired about the compound which we can separate from used lubricating oil, and which possesses strongly detergent properties. Oil B in the paper was a typical high V.I., solvent-extracted lubricating oil, and the acetone-insoluble material had an ultimate analysis of C, 82·5 per cent; H, 10·6 per cent; O, 6·0 per cent; S, 0·93 per cent. The molecular weight was 2800. Spectroscopic analysis failed to show any pronounced functional groups, and the oxygen is combined as hydroxyl and ester groups in the approximate ratio of 2 : 1. We have the general impression that the material is essentially a high molecular weight hydrocarbon, formed by polymerization of the lubricating oil molecule through some oxygen linkages.

Concerning Dr Grunberg's contribution, we have not been able to detect any influence of the metal surface upon the rate of oxidation of oils. A metal catalyst seems to function solely as a source of metal ions, but there may well be scope for a further investigation of this point.

It is, however, doubtful whether the critical temperature for deposit formation upon the hot plate is due to the change in the nature of the surface oxide film, since this temperature varies slightly from oil to oil, and, moreover, it may be raised by the addition of surface-active agents, such as the acetone-insoluble material obtained from oxidized oil.

D. Eve: In the first paper, the authors describe the determination of oil-insolubles and of the chloroform-soluble portion of these, but they do not give the experimental details of the method they used. Have those details been published?

In the fourth paper additive-depletion results are quoted, but how is the concentration of additive in the used oil measured? Chemical methods would be unsuitable, because one would not be able to distinguish between the original additive and its decomposition products.

Mr Hughes: It is difficult to lay down a generally applicable chemical method for measuring additive depletion, since the additives at present in use differ widely in chemical composition. Most current additives are metallic, however, and most of the metallic breakdown products of additives

are oil-insoluble. Consequently, a good method of measuring depletion is to measure the additive metal content of the used oil after filtration. This may not apply to all additives, but the method should be fairly widely applicable.

If one knows the chemical composition of the additive, it is frequently possible to devise a better method for assessing its depletion. The additive may, for instance, have some particular functional group for which one may analyse the used oil to assess depletion.

C. T. Wilshaw: A case of very unusual corrosion was reported from Australia, and the only pieces returned were a gudgeon-pin bush from one of our diesel engines. This phosphor bronze bush had undoubtedly corroded in a most unusual manner, the attack being of a pronounced inter-dendritic character. Furthermore, an analysis of the caked deposit in the oil groove in the rear of the bush showed that non-ferrous components in other parts of the engine and, in particular, the copper–lead bearings had also been attacked. There was a possibility that the gear oil had contaminated the engine oil in this particular tractor application. Is it possible that the contamination of an engine oil by the gear oil can introduce any unusual corrosive factor?

Dr Matthews: I am afraid that it is impossible to give a specific answer without some knowledge of what additives were contained in the gear oil, and of the temperature. E.P. additives can cause corrosion, but whether corrosion occurs is dependent on a combination of three factors, namely: the composition of the bearing metal; the composition of the additive; and the temperature of the metal surface.

H. E. Styles: Regarding the dependence of the carbon content of the used oil upon mixture strength in the combustion chamber, there is another possibility which may influence the carbon content. If samples of oil are taken from a very large number of engines which are nominally the same and whose mixture strength is controlled within fairly narrow limits, one finds very big variations in the individual carbon contents. The explanation is that the carbon contents of the oil can, of course, be considerably influenced by the mechanical condition of the engine. There is considerable variation in the amount of blowby, etc. Hence there are at least three factors which may affect the carbon content of the used oil: mixture strength; cylinder wall temperature; and the mechanical condition of the engine itself.

Dr Matthews: I agree that the mechanical condition of the engine will determine to some extent the amount of contamination entering the oil. But it is extremely difficult to get combustion-chamber smoke particles into the oil by simple contact between the oil and the smoke. It is necessary to rub the carbon into the oil, and the efficiency of this rubbing process will depend largely on the clearances involved. The general state of the combustion chamber may also affect the combustion process, which again will be reflected in the deterioration of the oil. In these papers it has been assumed that the mechanical condition factor is a constant.

M. F. MOHTADI: We have carried out micrograph analysis of a number of used lubricating oils, and they have not been found to be of a monodisperse nature as in the micrographs illustrated.

The electrokinetic properties of used lubricating oils have been investigated, and we find that the carbon particles suspended in additive oils move electrophoretically in an electric field, and can be forced to move in any direction. Therefore, by employing a suitable additive with a used lubricating oil which has not been flocculated and setting up an electric field, the water and carbonaceous materials can be separated from the oil.*

DR MATTHEWS: It was surprising to find that used engine oils were apparently of a monodisperse character. This does not mean that all the particles are of exactly the same size, but that on a statistical basis the majority of the particles fall within rather narrow size limits. Hence, it will be possible to find a few very small particles with an electron microscope. Before accepting such evidence as disproving the monodisperse character of the particles as a whole, however, it is necessary to prove that the number or weight of these particles is of a magnitude which will change the shape of the particle-size distribution curve. Also, the treatment to which the sample is subjected in order to make observations may radically affect the size distribution of the particles, and this is a very important matter when working with an electron microscope. It is most likely that the individual particles, which have been examined in their original state in used oils by both microscopic and sedimentation methods, are actually tightly bound aggregates of much smaller particles. Some disaggregation of these particles could occur in the slide preparation for the electron microscope, or in the electron beam itself.

Other investigators have demonstrated that electrophoresis and associated phenomena can occur in dispersions of various solid materials in hydrocarbon liquids. In no case, however, have these phenomena been satisfactorily demonstrated with actual used engine oils. We have tried to make such observations ourselves in used oils, admittedly without constructing any special apparatus for the experiments, but failed to observe anything which could be interpreted as being the result of electrophoresis or its allied phenomena. I think the question of whether ionization phenomena occur in used engine oils still remains to be answered.

R. A. FRASER: Dr Matthews mentions that several tests were carried out in a motored engine and that very low figures were found for the concentration of inorganic oil-insolubles. I should like to ask at what temperature the jacket and sump were maintained. If the engine were motored and not running under ordinary conditions, the temperature may have been much lower, and that may have had an effect.

In connexion with the oil-insoluble materials in the used oils in diesel engines, has any work been done on the effect of the sulphur content of the fuel? If the fuel has such a large effect on the quality of the oil in the crankcase, it is highly probable that the sulphur content would affect the composition of the oil-insolubles.

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* Garner, F. H., Mohtadi, M. F., and Nutt, C. W. *J. Inst. Petrol.*, 1952, **38**, 986–97.

DR MATTHEWS : In the motored engine tests, the jacket temperature was maintained at 260° C and the sump oil temperature at 120° C, which are extremely severe temperature conditions, conducive to the formation of oxidation sludge, if this is capable of forming at all.

We have not studied the effect of fuel sulphur on oil deterioration from the lubricating oil end, but some years ago we investigated the effect of fuel sulphur on the nature of the exhaust soot in diesel engines,* and found that the sulphur products of combustion are strongly adsorbed to the particles, and that they apparently have a remarkable effect on the nature of the soot. Thus, the higher the sulphur content of the soot, the lower was its packing volume. Since these soot particles are the nuclei of the used oil particles, it follows that fuel sulphur may have a definite effect on the colloidal behaviour of the used oils.

J. ROMNEY : By mathematical means, the authors of the last paper are able to derive the optimum concentrations of detergent additives for oils. Surely, the amount of detergent additive required depends on the amount of insolubles formed, because it is understood that the detergent additive wraps itself round the various carbon particles by being adsorbed or sorbed on them. That being the case, the quantity of additive required should depend on the number of these carbon particles. Since the authors themselves have shown that the number of carbon particles and quantity of insolubles vary so very much from engine to engine, I find it difficult to see how a mathematical treatment can arrive at the amount of additive required to cover what is, in fact, an unknown factor. Perhaps the authors could explain this further.

MR HUGHES : One cannot, of course, produce an oil having the optimum additive concentration for each engine. However, in a particular type of operation, the amounts of carbon and other contaminants produced should not vary greatly. Neither should the rates of additive depletion. From a knowledge of the average, or perhaps most severe, rates of contamination and depletion, it is possible to design a lubricant to meet the requirements of any particular type of service. This, of course, assumes that the engine is being run correctly. If it is being run under conditions far from those laid down by the manufacturers, or if its mechanical condition is poor, then the designed lubricant may well prove inadequate.

The mathematical approach suggested in our paper enables an estimate of additive requirements for a given type of service to be made, rather than guessing the requirements.

THE CHAIRMAN : We have this evening listened to a most valuable summary of an interesting group of papers. The fact that mathematics can be introduced into the subject is the modern trend, and the expression $1 - e^{-Kt}$ is one which I have come across in various spheres—in operational research, for example, as well as in laboratory investigations. I am sure

* Broeze, J. J., and Wilson, A. *Auto. Engr*, **39**, 118.

that I am expressing the feelings of all of you in saying how very much indebted we are to Dr Matthews and his colleagues for the interesting papers we have had tonight and for the way in which they were presented. I will ask you to show your appreciation in the usual manner.

(The vote of thanks was heartily accorded.)

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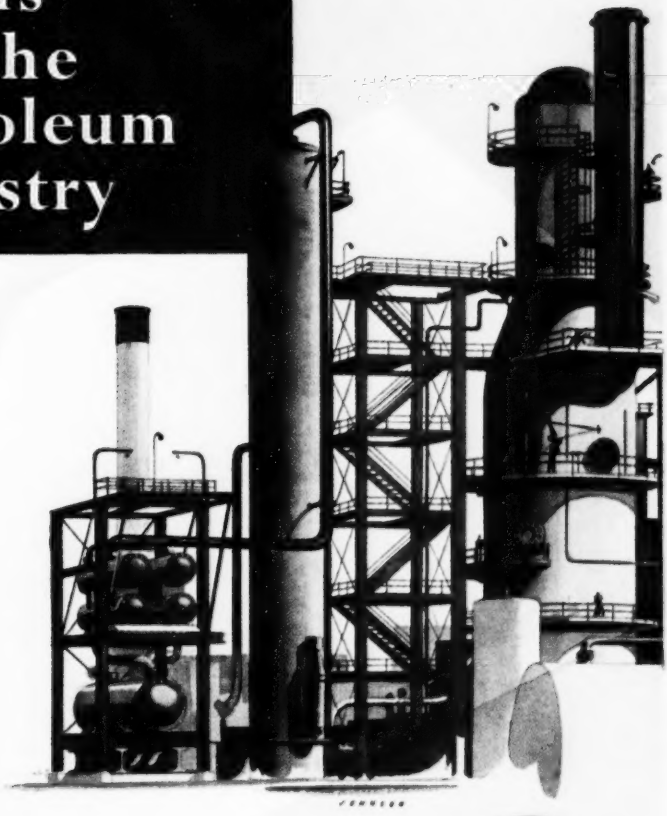

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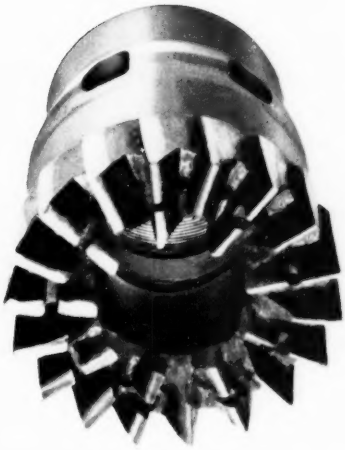

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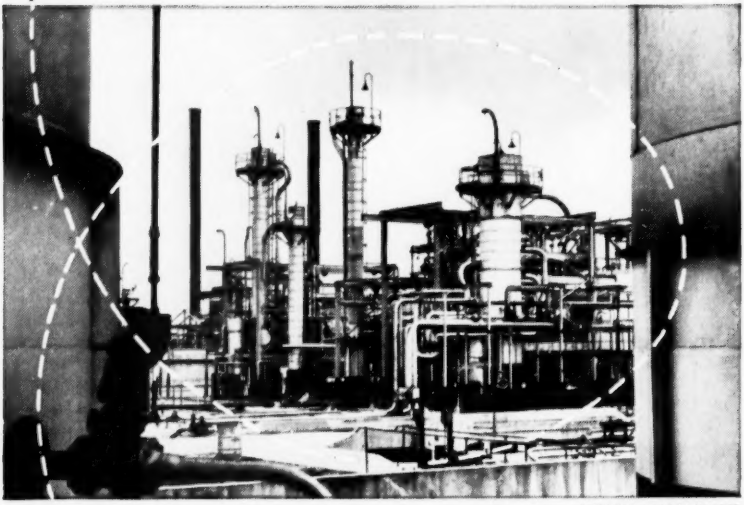

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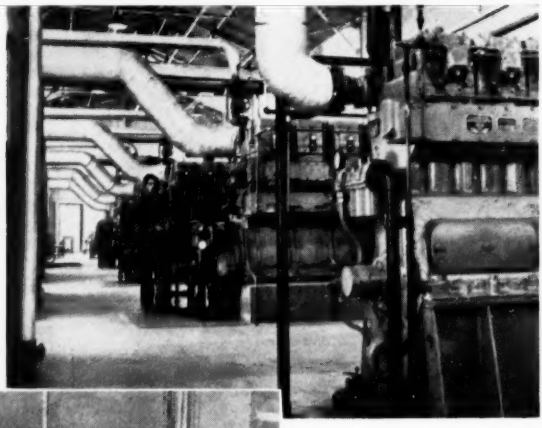

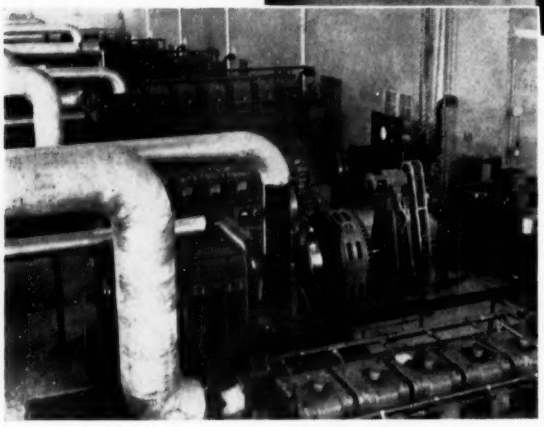

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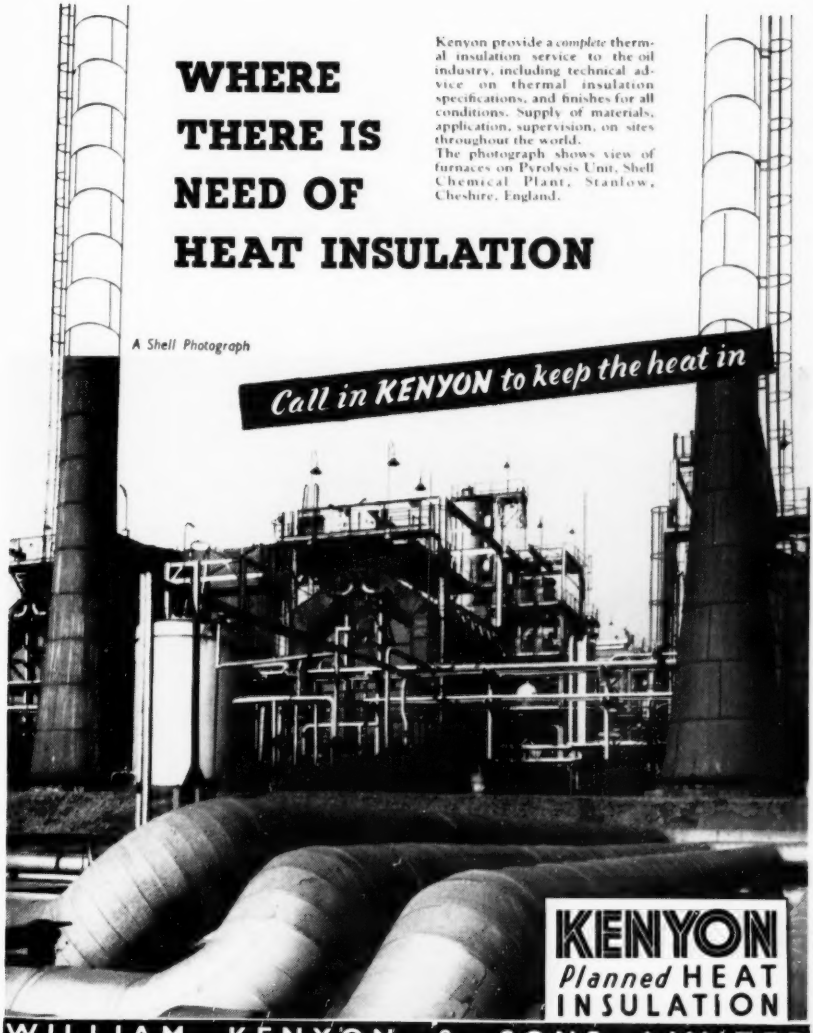

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. . . and that Kellogg is currently erecting a unique gasoline-from-coal synthesis plant which, along with fuels, produces a variety of chemicals that will be purified in special process equipment.

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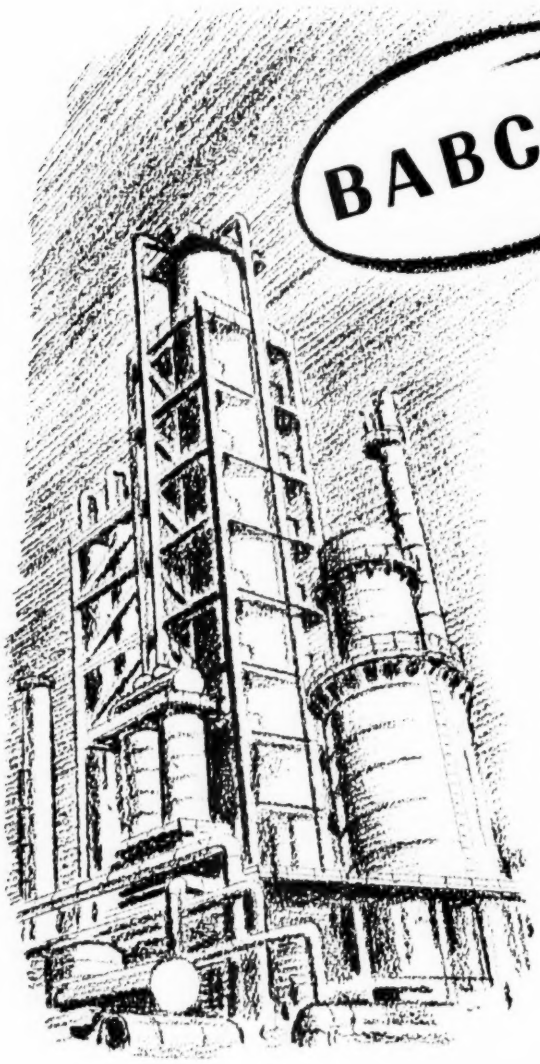

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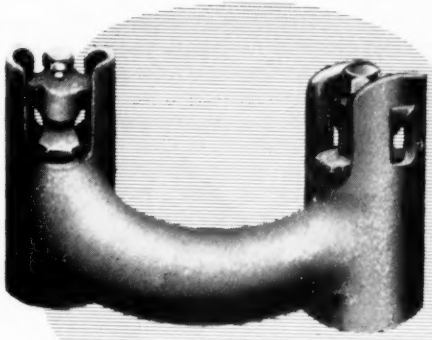

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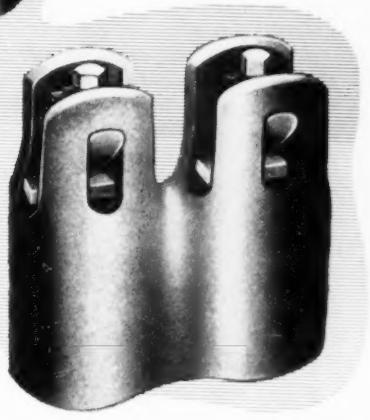

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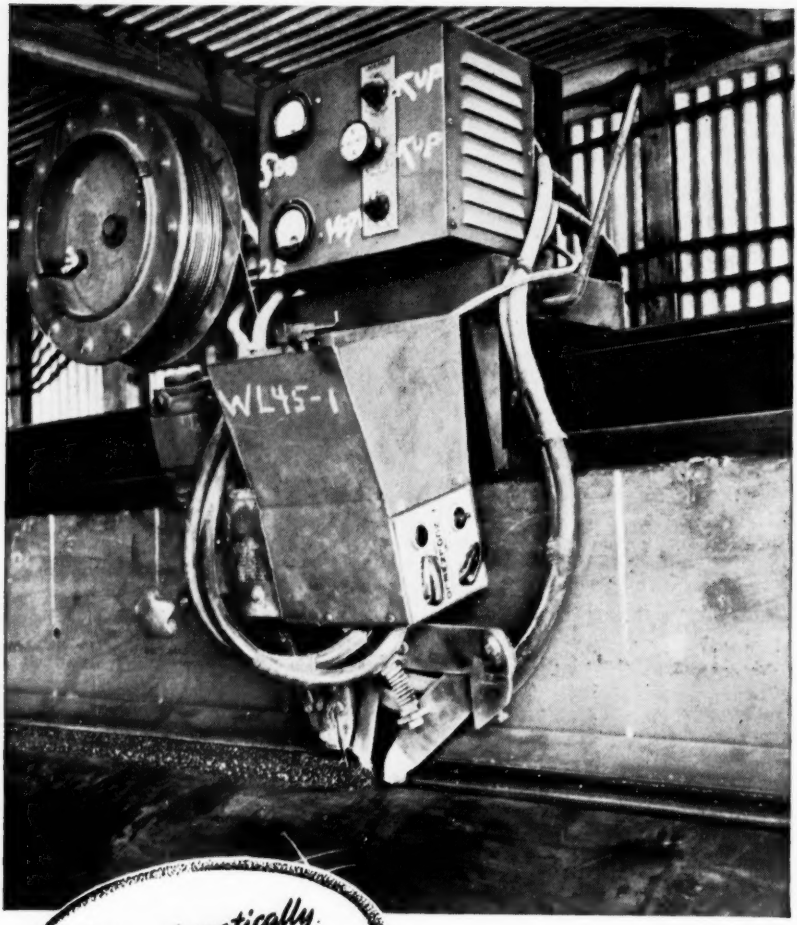

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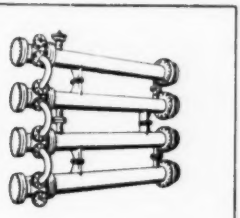

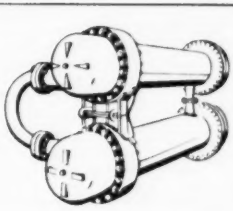

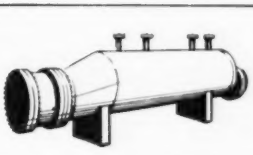

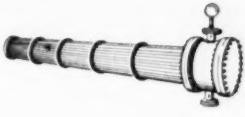

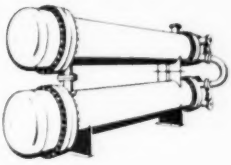

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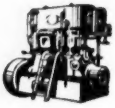

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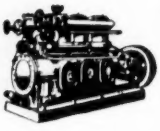

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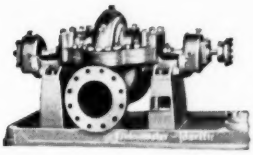

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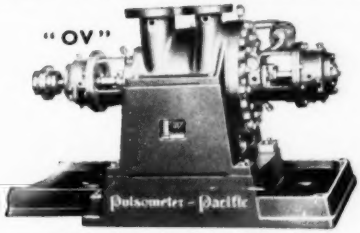

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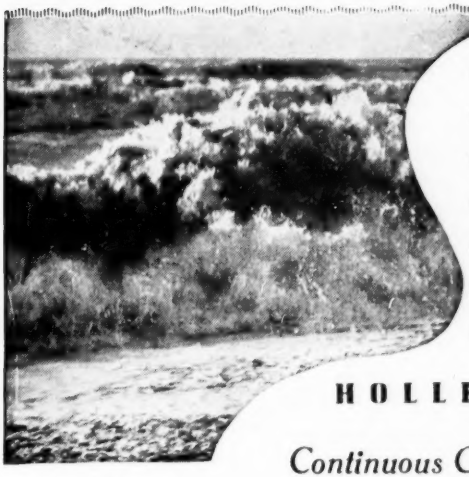

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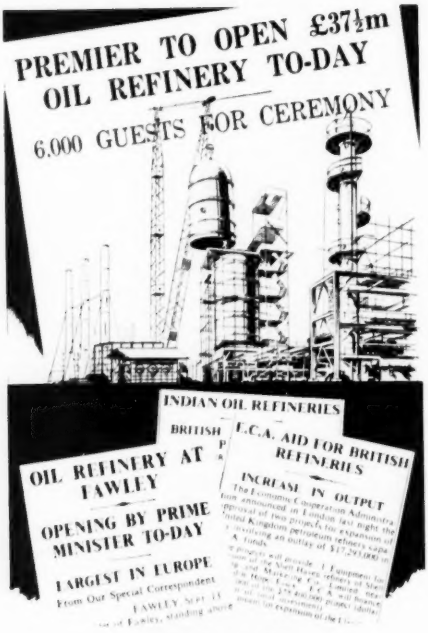

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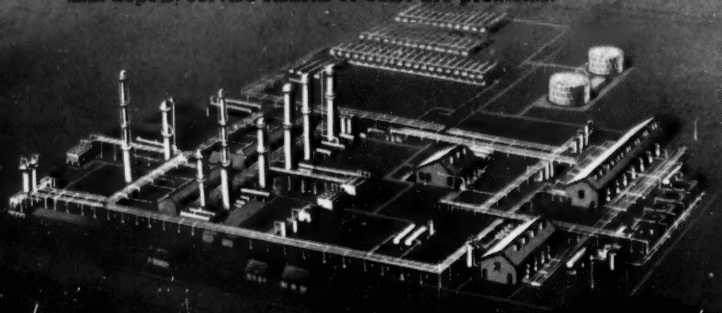

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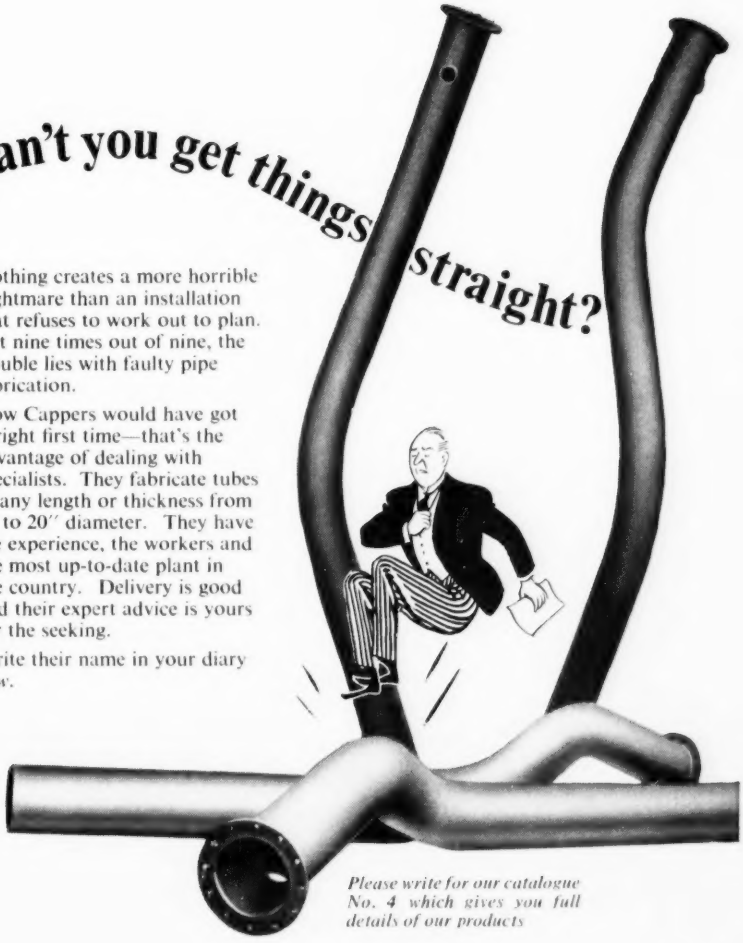

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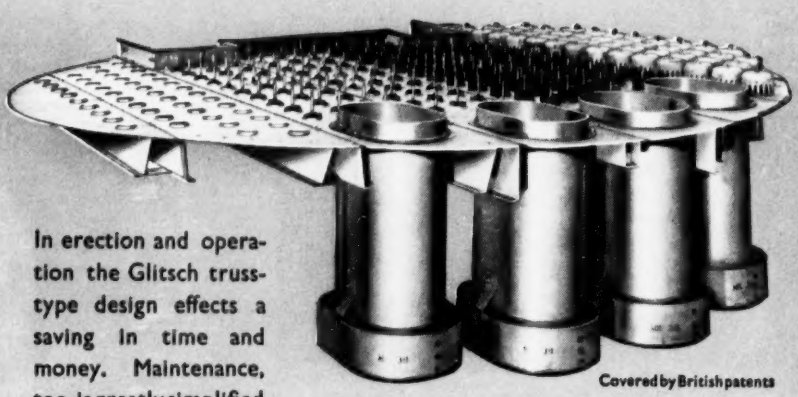

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